Lepton Flavor Violation
Muon to Electron Conversion
COMET and PRISM
at J-PARC

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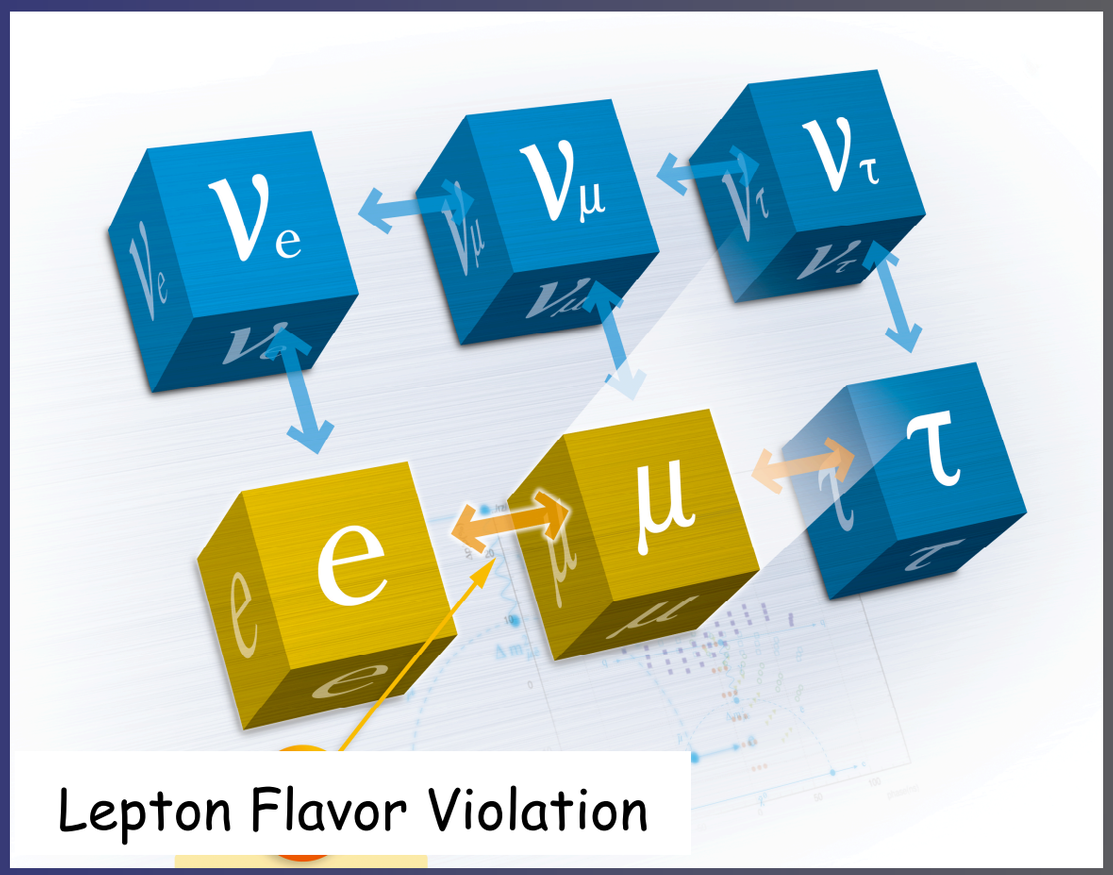
NuFACT2008
Valencia Spain



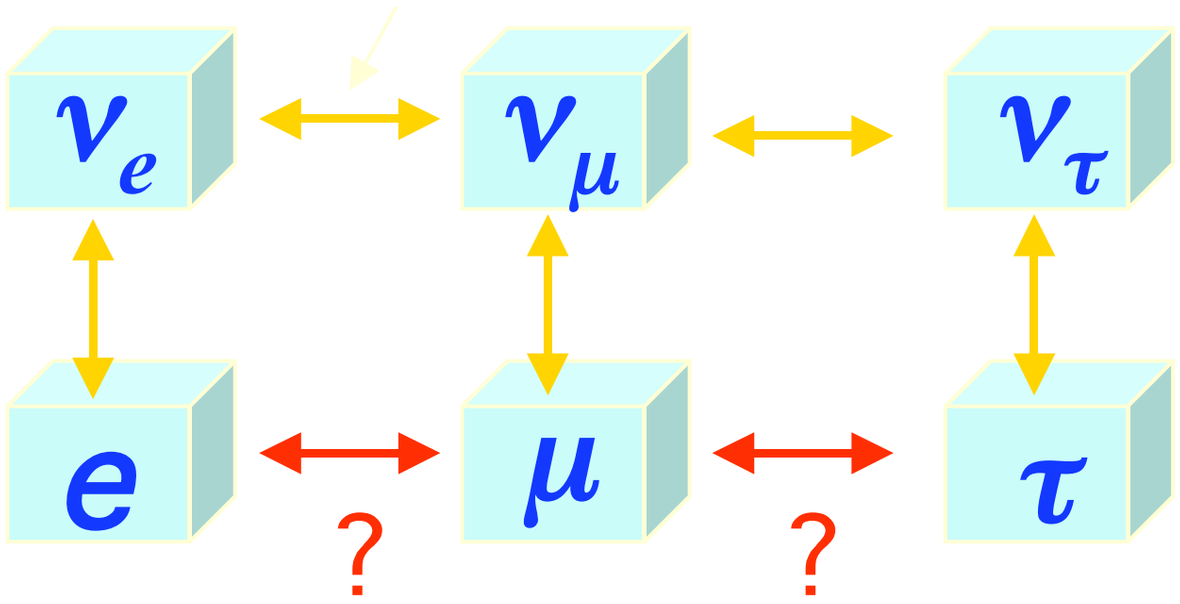
Outline

- Physics Motivation for Lepton Flavor Violation (LFV)
- LFV Experiments
- New Experimental Proposals in Japan
- COMET
- PRISM
- Summary

LFV Physics Motivation

Lepton Flavor Violation (LFV) of Charged Leptons

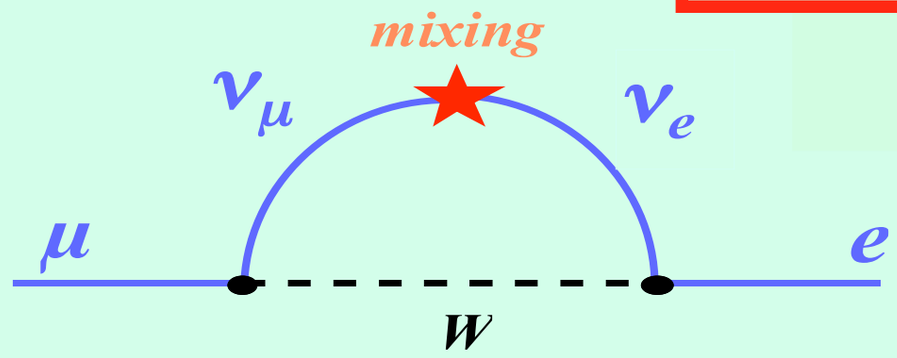
LFV of neutrinos
(confirmed)



LFV of charged leptons
(not observed yet)

What is the contribution from neutrino mixing in the Standard Model?

$\propto (m_\nu / m_W)^4$



Very Small (10^{-52})

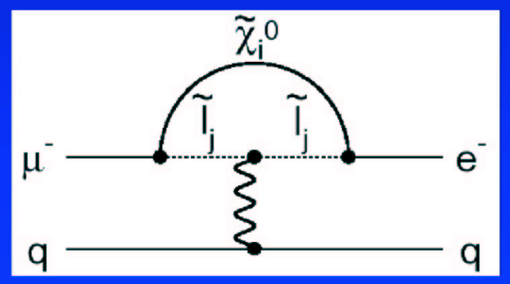
Sensitive to new Physics
beyond the Standard Model

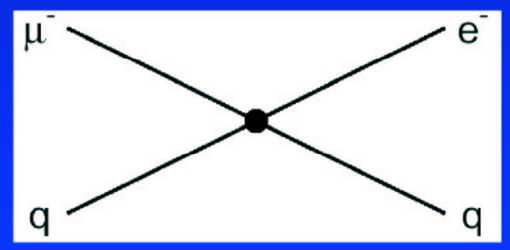
Various Models Predict Charged Lepton Mixing.

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}





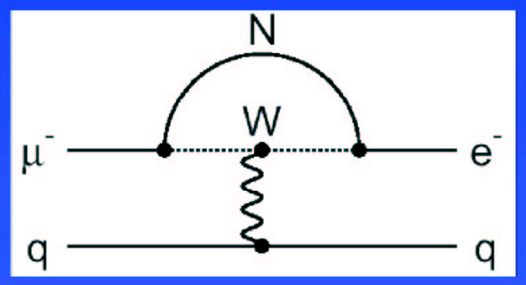
Compositeness

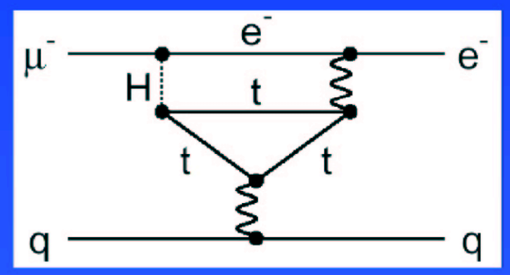
Λ_c = 3000 TeV

Heavy Neutrinos

$|U^*_{\mu N} U_{eN}|^2$ =

8×10^{-13}





Second Higgs doublet

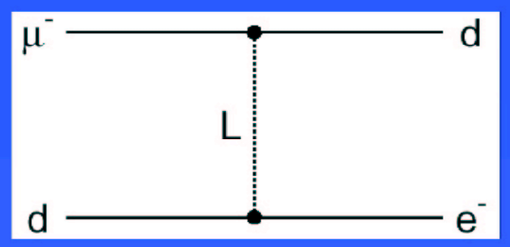
$g_{H\mu e} = 10^{-4} \times g_{H\mu\mu}$

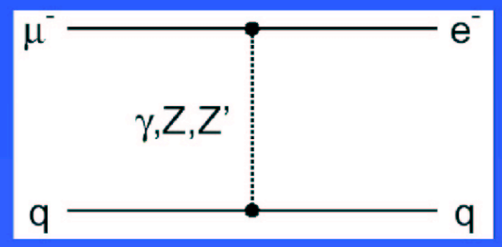
Leptoquarks

M_L =

$3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2

After W. Marciano





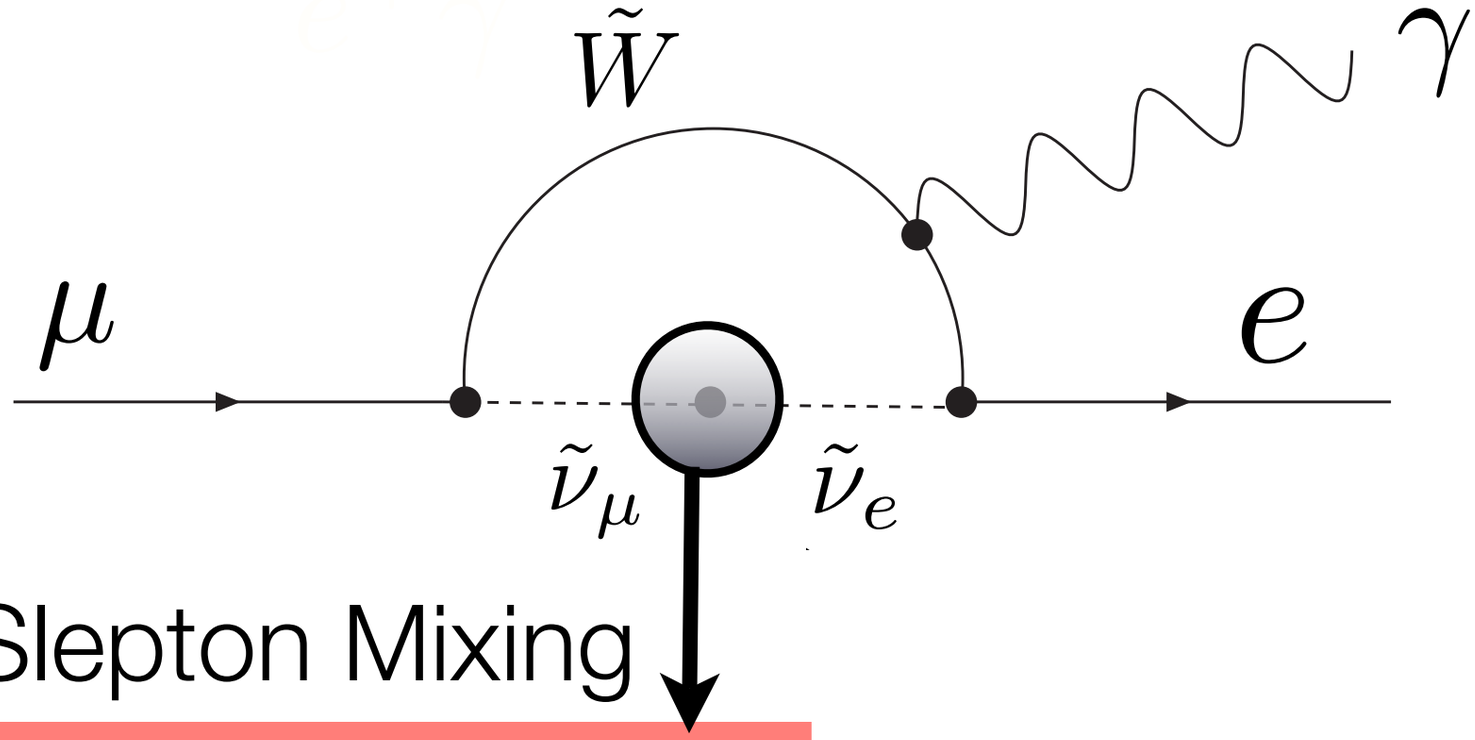
Heavy Z', Anomalous Z coupling

$M_{Z'}$ = 3000 TeV/c^2

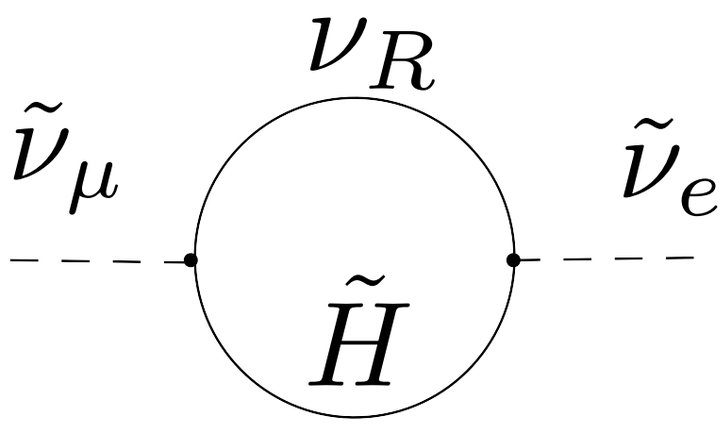
B($Z \rightarrow \mu e$) < 10^{-17}

LFV in SUSY Models

an example diagram



Slepton Mixing



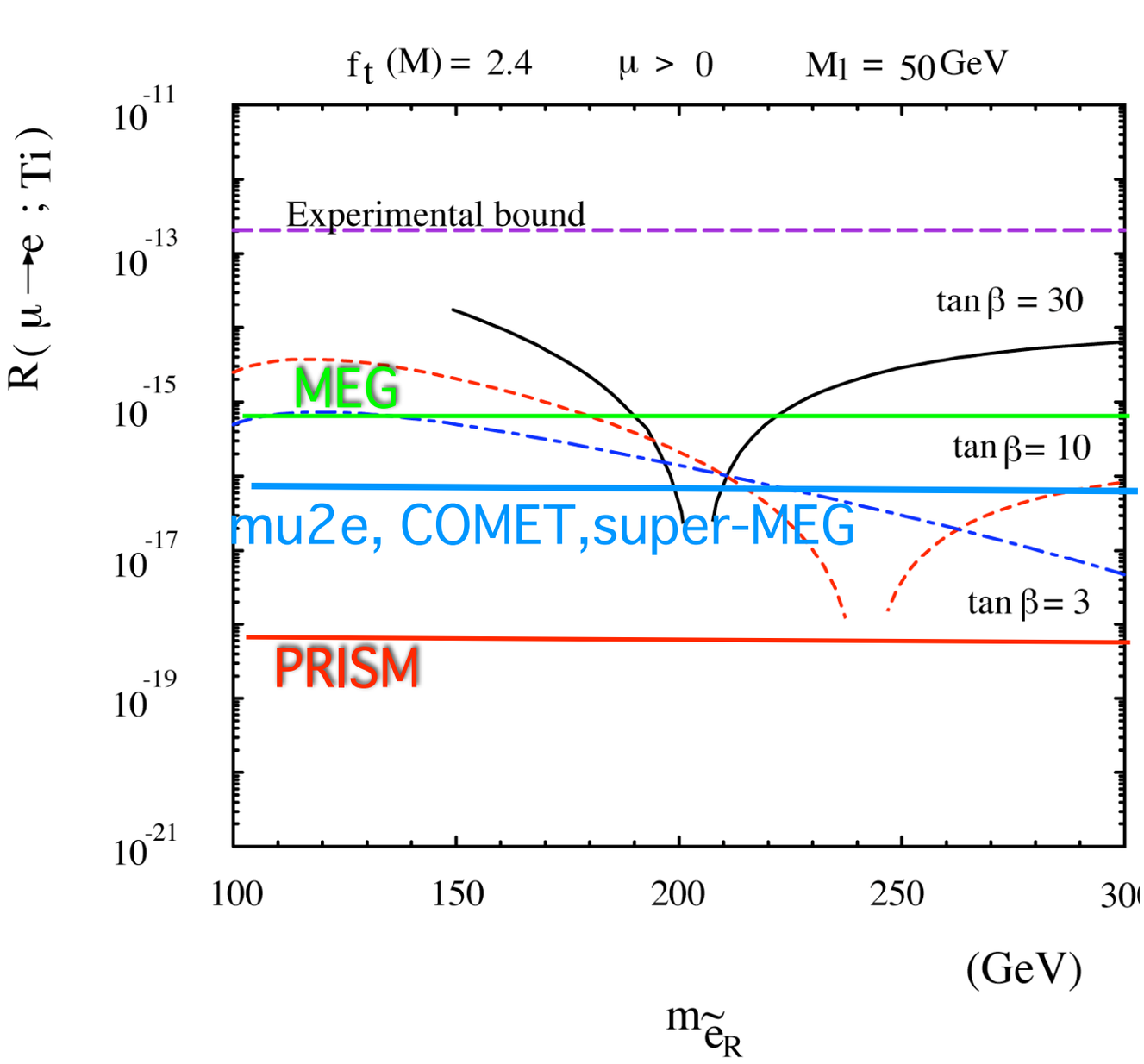
Features

- The decay rate is not too small, because it is determined by the SUSY mass scale.
- But, it contains the information at 10^{16} GeV through the slepton mixing.
- It is in contract to proton decays or double beta decays which need many particles.

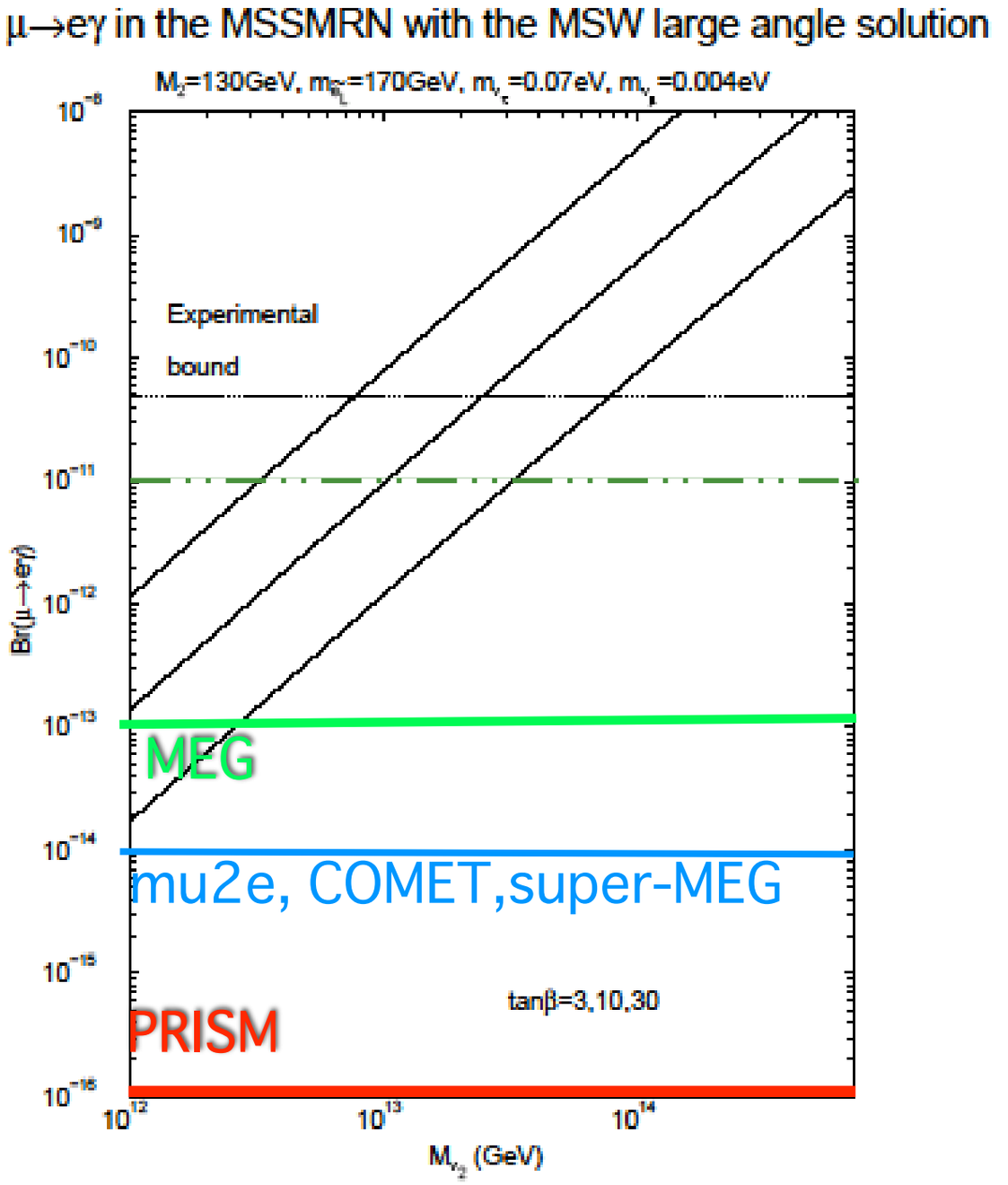
Through quantum corrections, LFV could access ultra-heavy particles such as ν_R (~10^{12}-10^{14} GeV/c^2) and GUT that cannot be produced directly by any accelerators.

SUSY GUT and SUSY Seesaw

SUSY Predictions for LFV with Muons



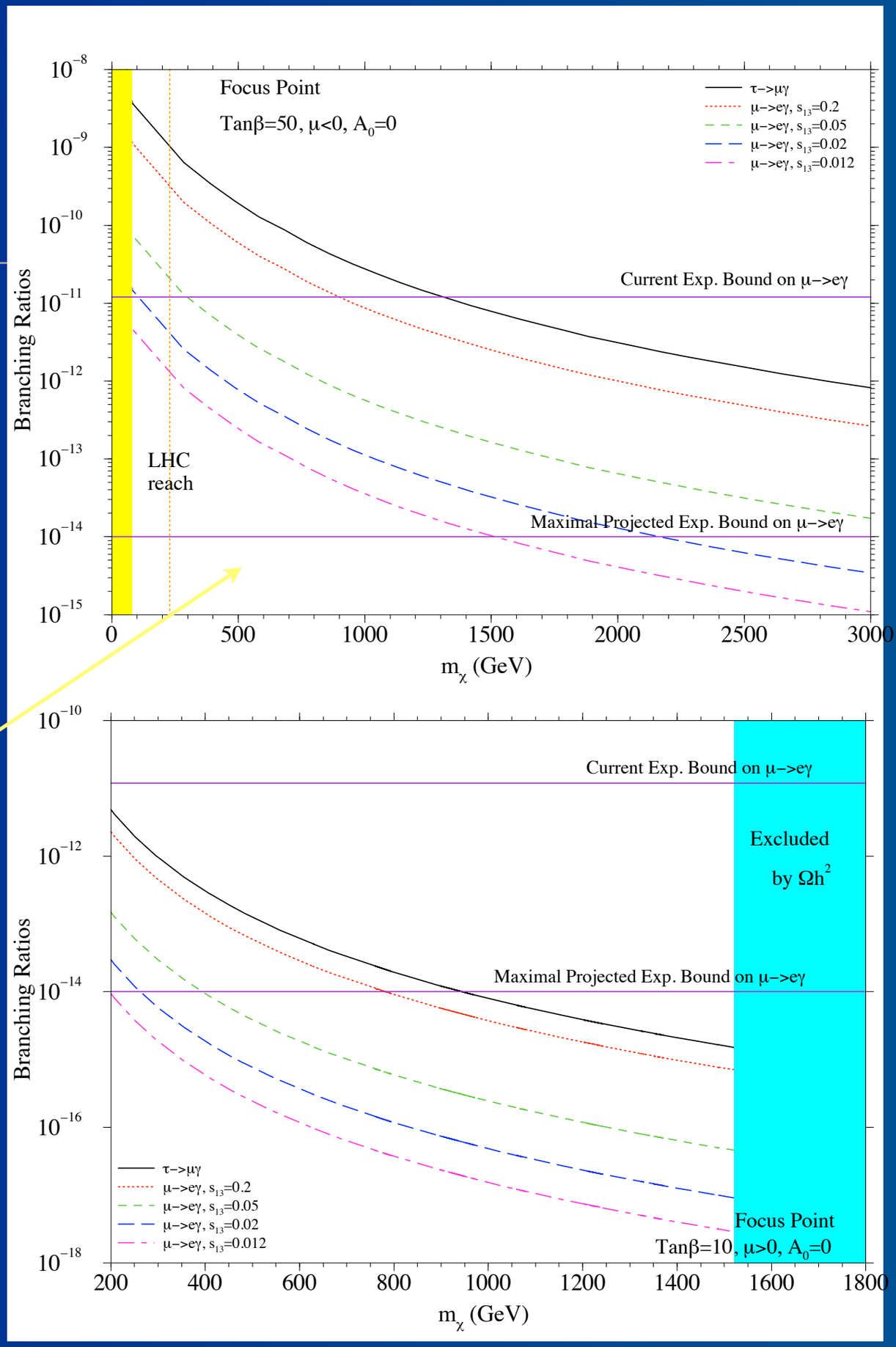
SU(5) SUSY GUT



SUSY Seesaw Model

Complementarity to LHC (mSUGRA)

- In mSUGRA, some of the parameter regions, where LHC does not have sensitivity to SUSY, can be explored by LFV.
- Bench mark points
  - coannihilation strip
    - LHC covers and LFV does.
  - A-pole funnels
    - LHC partially covers and LFV does cover.
  - Focus point
    - LHC does not cover and LFV does cover.



Short Summary of Motivation : LFV, Energy Frontier and SUSY

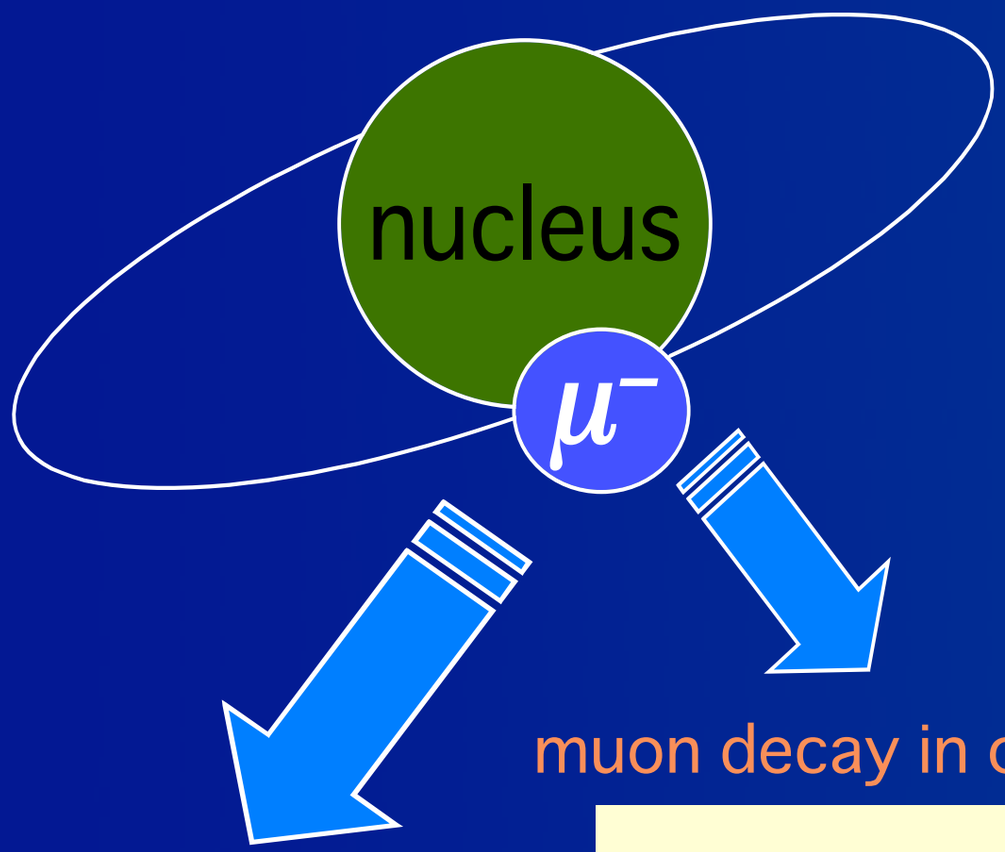
- In SUSY models, charged lepton mixing is sensitive to slepton mixing.
- LHC would have potentials to see SUSY particles. However, at LHC nor even ILC, slepton mixing would be hard to study in such a high precision as proposed here.

- Slepton mixing is sensitive to either (or both) Grand Unified Theories (SUSY-GUT models) or neutrino seesaw mechanism (SUSY-Seesaw models).
- If LFV sensitivity is extremely high, it might be sensitive to multi-TeV SUSY which LHC cannot reach, in particular SUSY models.

LFV Experiments

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

lepton flavors changes by one unit.

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N')}$$

μ-e Conversion
Signal and Backgrounds

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

- Signal
  - single mono-energetic electron

$$m_\mu - B_\mu \sim 105 MeV$$

  - coherent process (the same initial and final nucleus)

$$\propto Z^5$$

- Backgrounds
  - Muon decay in orbit
    - Endpoint comes to the signal region

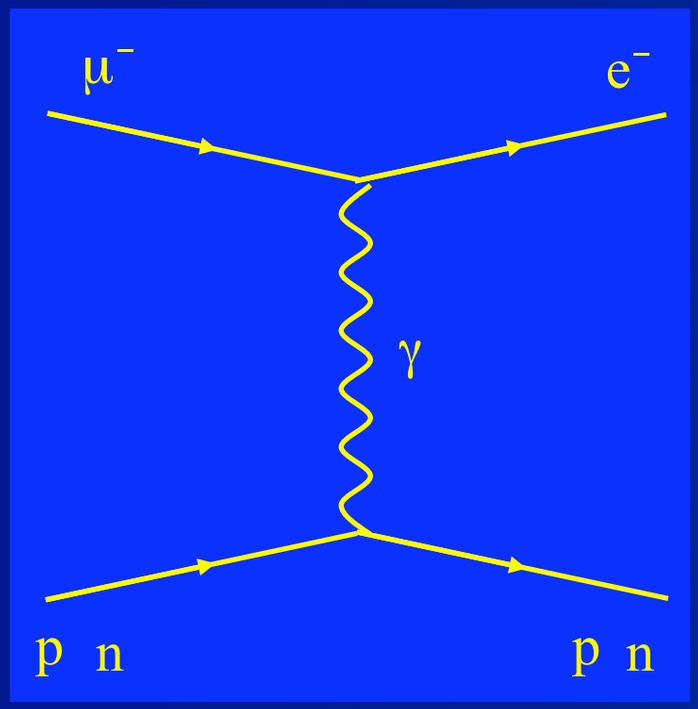
$$\propto (\Delta E)^5$$

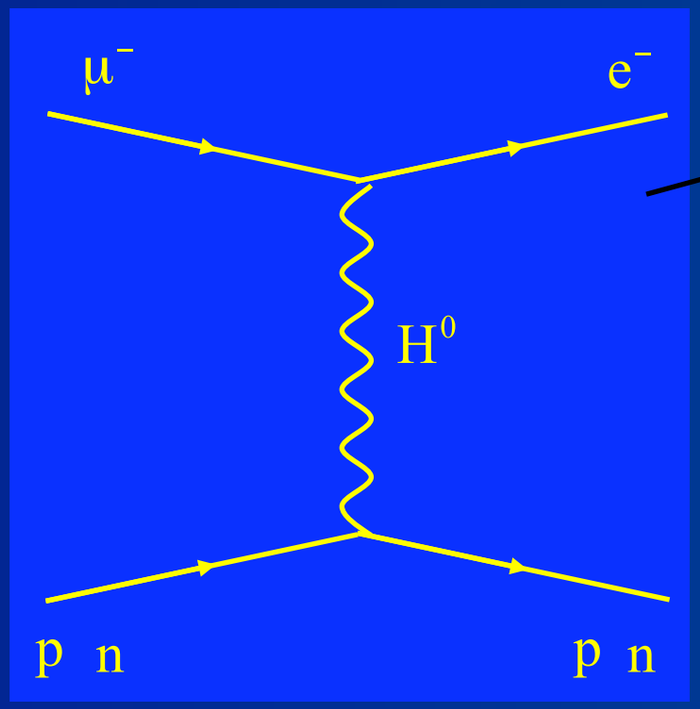
  - Radiative muon capture
  - Radiative pion capture
    - pulsed beam required
    - wait until pions decay.
  - Electrons from muon decays in flight
  - Cosmic rays
  - and many others

Comparison between μ→eγ and μ-e Conversion (Physics sensitivity)

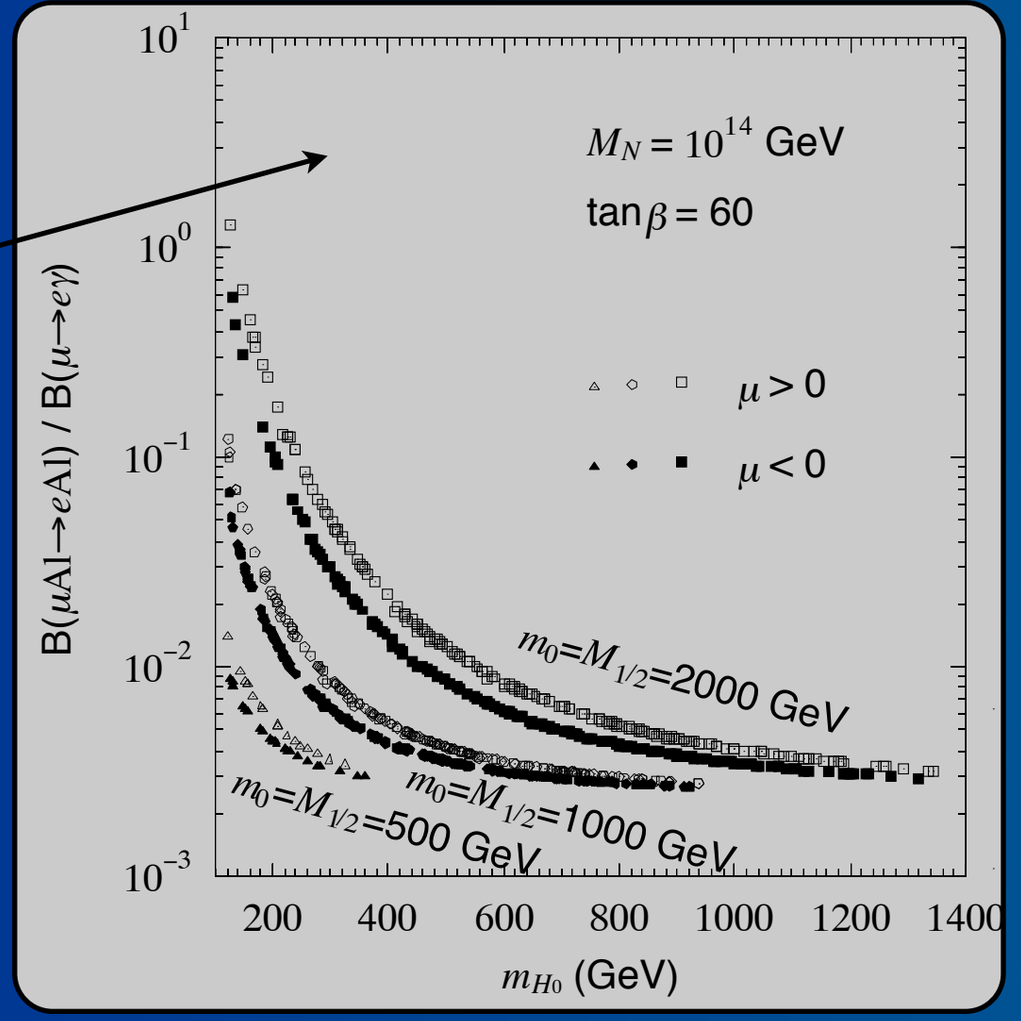
Photonic and non-photonic (SUSY) diagrams

	photonic	non-photonic
• μ→eγ	yes (on-shell)	no
• μ-e conversion	yes (off-shell)	yes





$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} \sim \frac{1}{100}$$



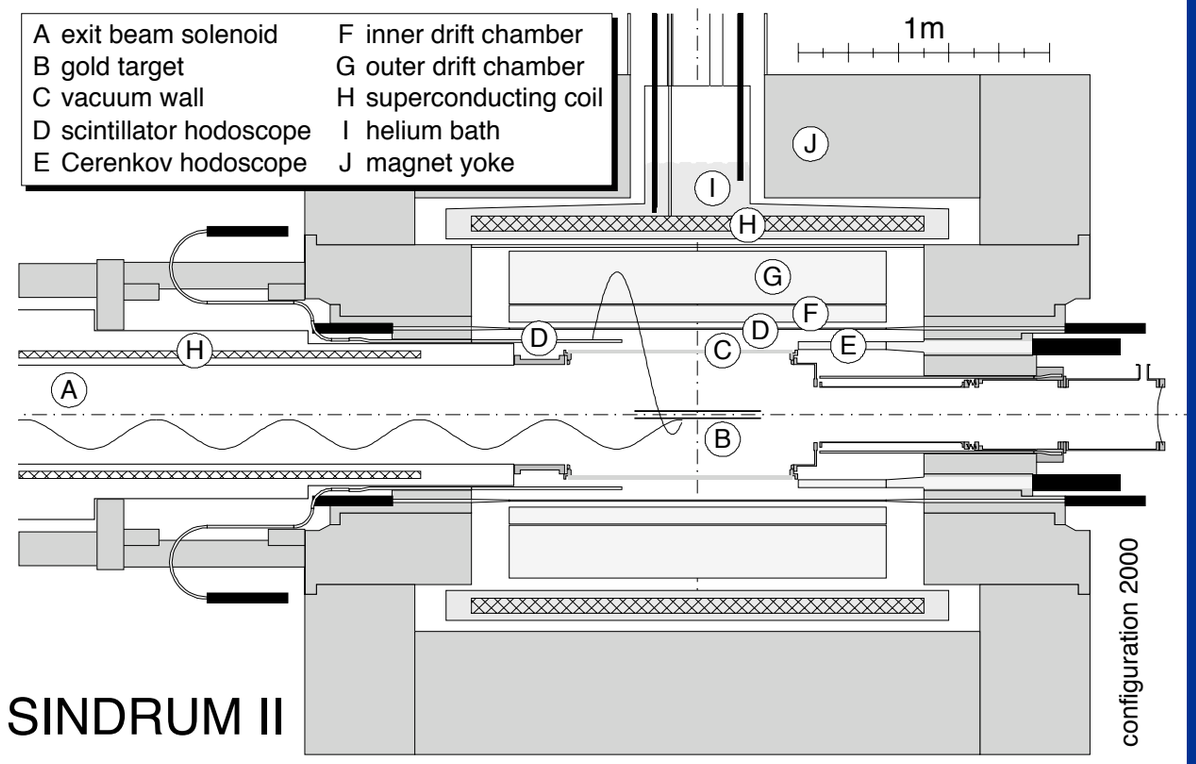
Comparison between μ→eγ and μ-e Conversion (Experimental)

	background	challenge	beam intensity
• μ→eγ	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

- μ→eγ : Accidental background is given by (rate)^2. The detector resolutions have to be improved, but they (in particular, photon) would be hard to go beyond MEG from present technology. The ultimate sensitivity would be about 10^{-14} (with about 10^8/sec) unless the detector resolution is radically improved.
- μ-e conversion : Improvement of a muon beam can be possible, both in purity (no pions) and in intensity (thanks to muon collider R&D). A higher beam intensity can be taken because of no accidentals.

μ-e conversion might be a next step.

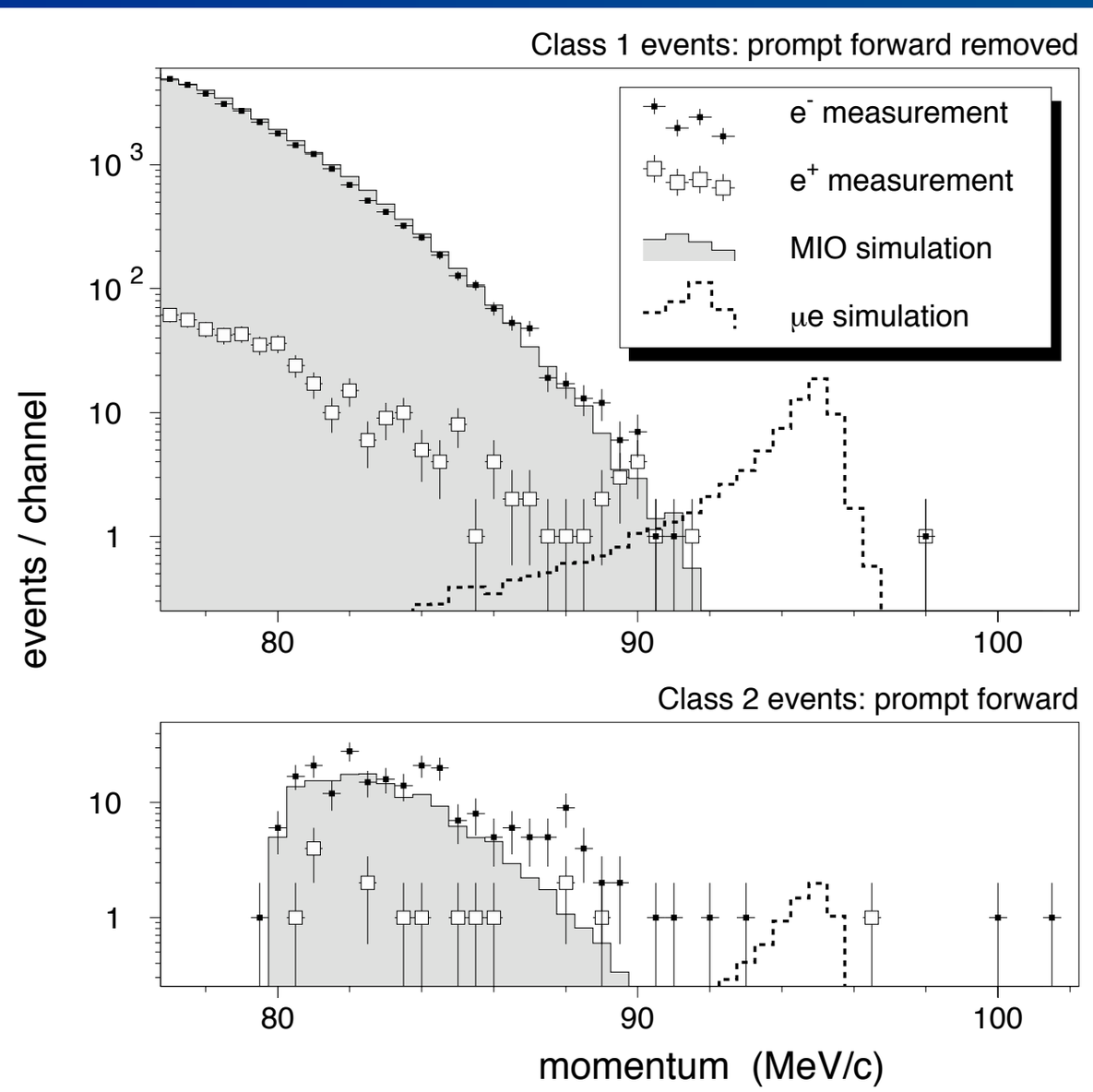
The SINDRUM-II Experiment (at PSI)



SINDRUM-II used a continuous muon beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



Potential Improvements for Next Generation μ-e Conversion Experiments

Reduction of beam-related backgrounds

Beam pulsing is needed and the measurement during beam pulses is made. Pulse separation should be about 1μsec.

Narrow beam energy spread

A thinner muon stopping target is needed to improve the energy resolution of electron detection. And therefore the beam energy spread should be narrow.

High muon beam intensity

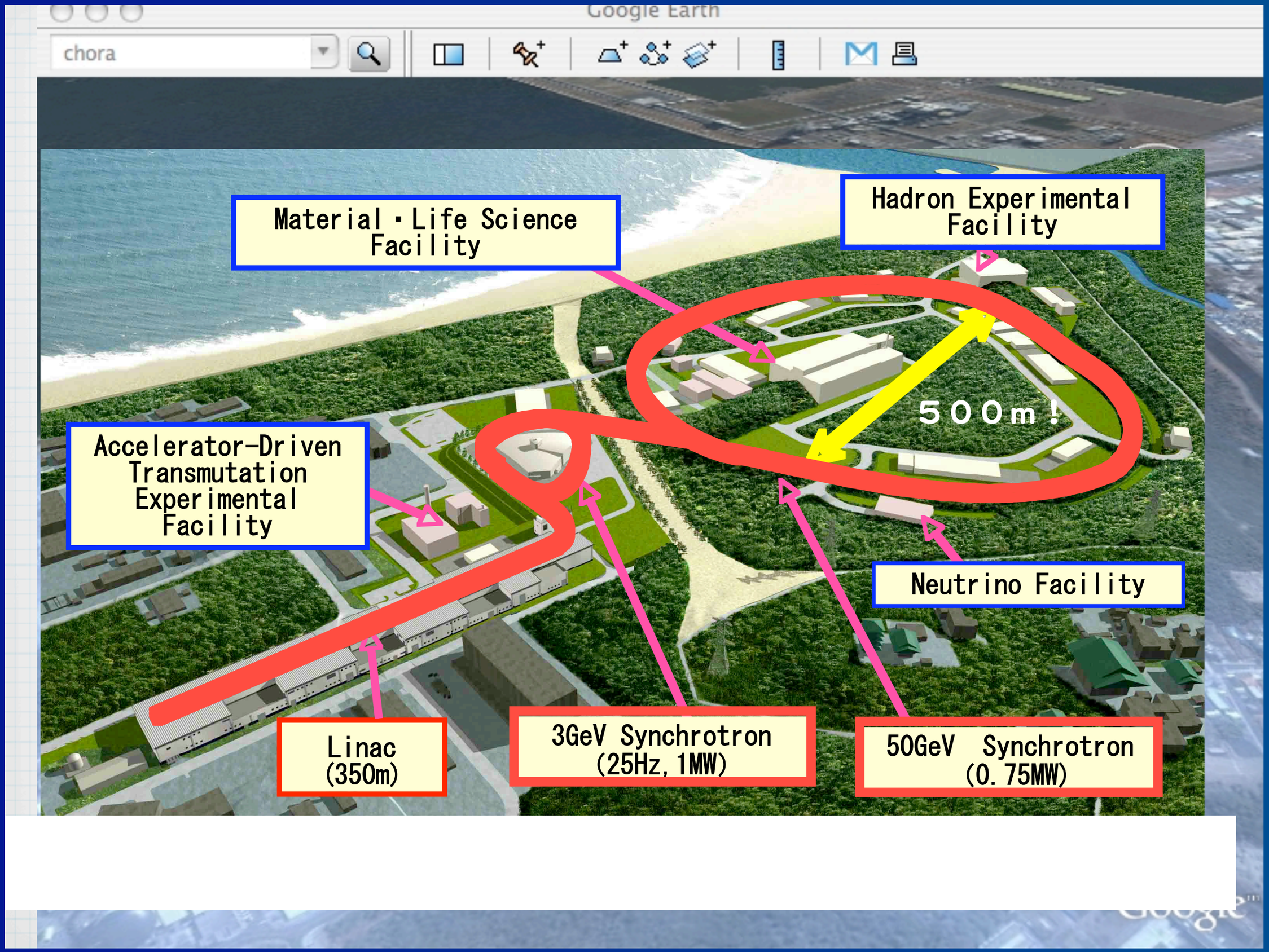
Pion capture and muon transport by superconducting solenoids would provide high beam intensity,

Reduction of pions in a muon beam

A muon beam line should be sufficient long to eliminate pions in a muon beam.

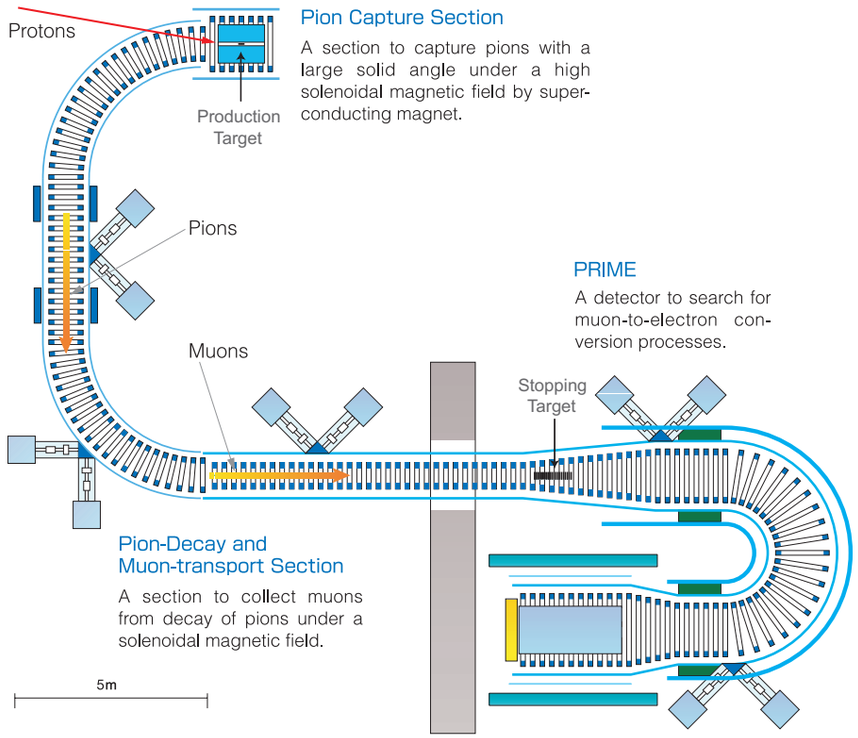
New Experimental Proposals in Japan

J-PARC at Tokai, Japan



Long Future Prospects : From COMET to PRISM

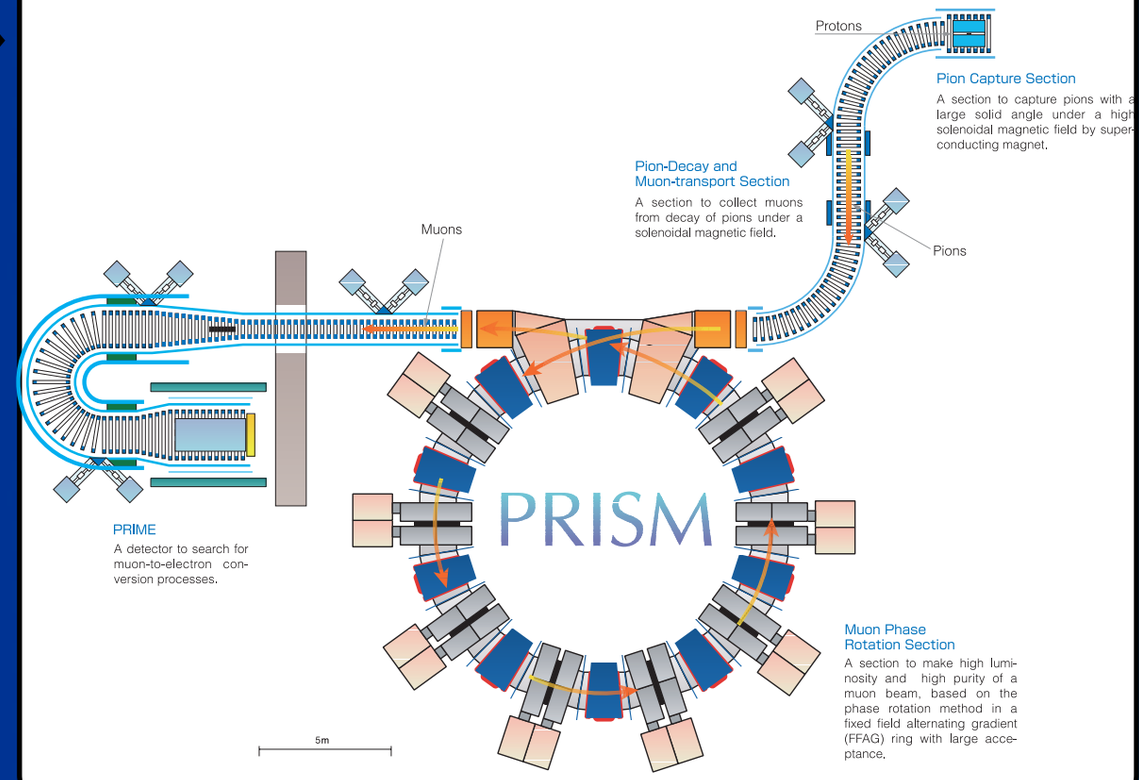
COMET



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

PRISM



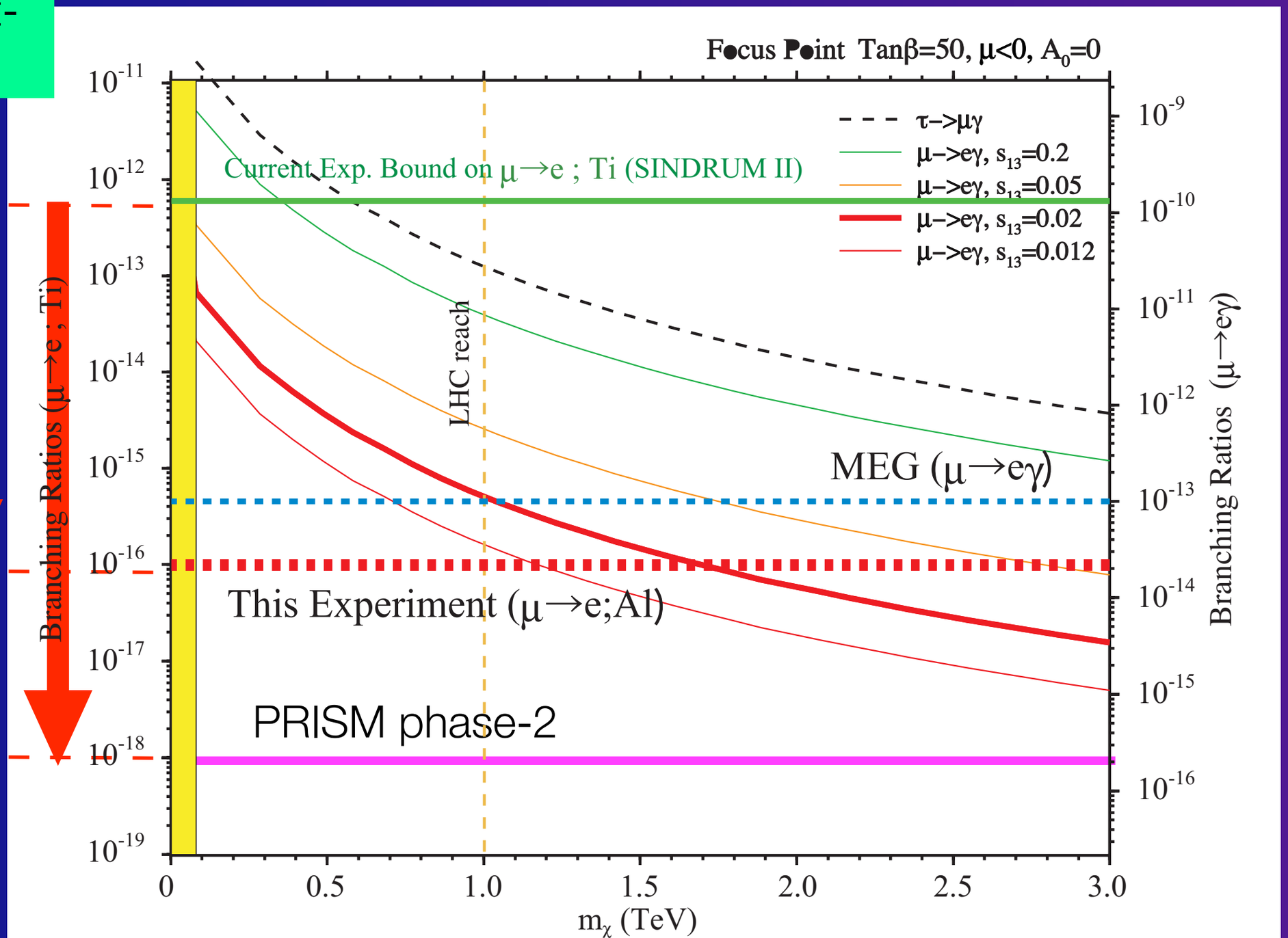
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

mSUGRA with right-handed neutrinos

will be improved by a factor of 10,000.

will be improved by a factor of 1000,000.



Sensitivity Goal

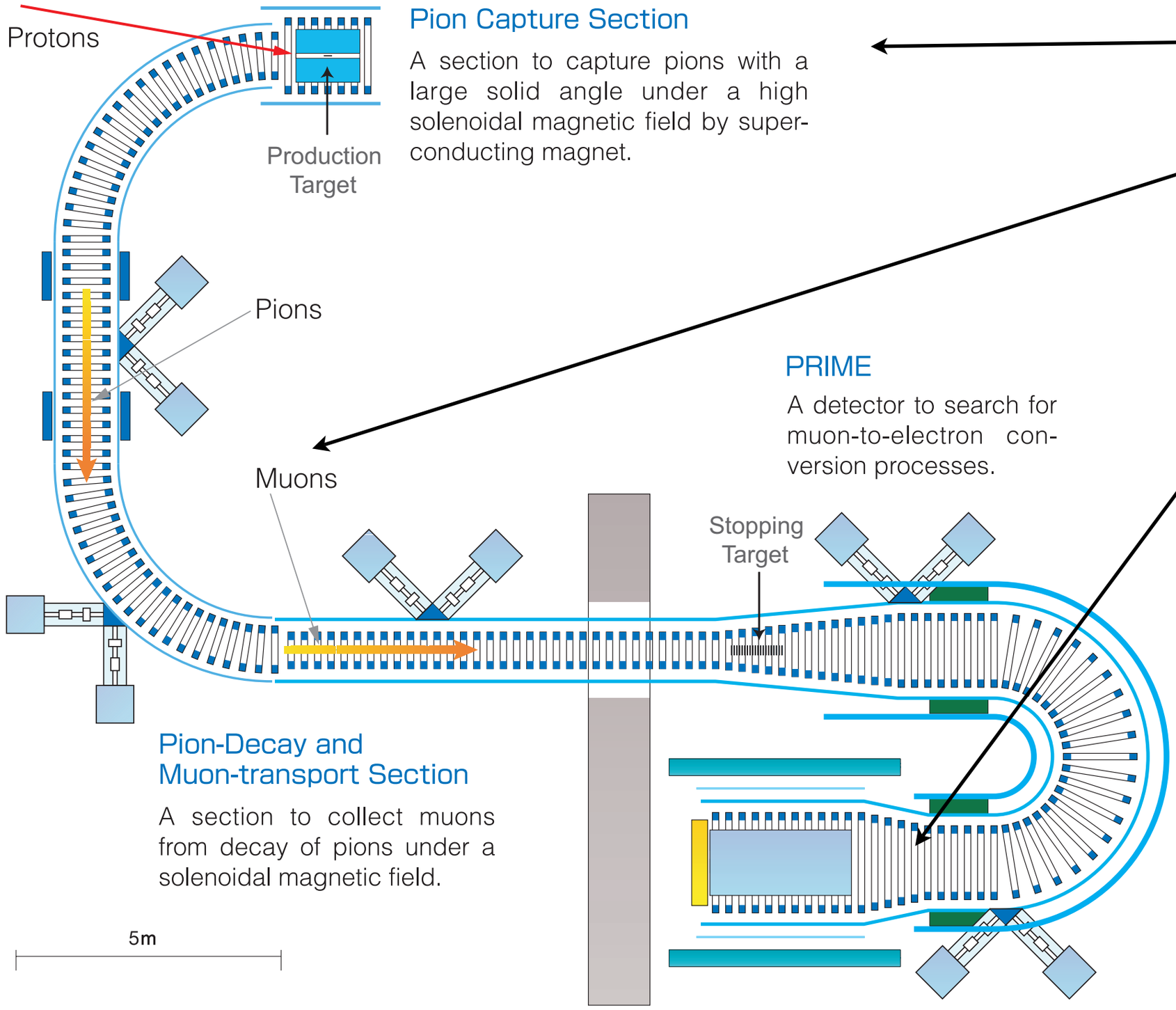
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

COMET

COMET (COherent Muon to Electron Transition) in Japan

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$



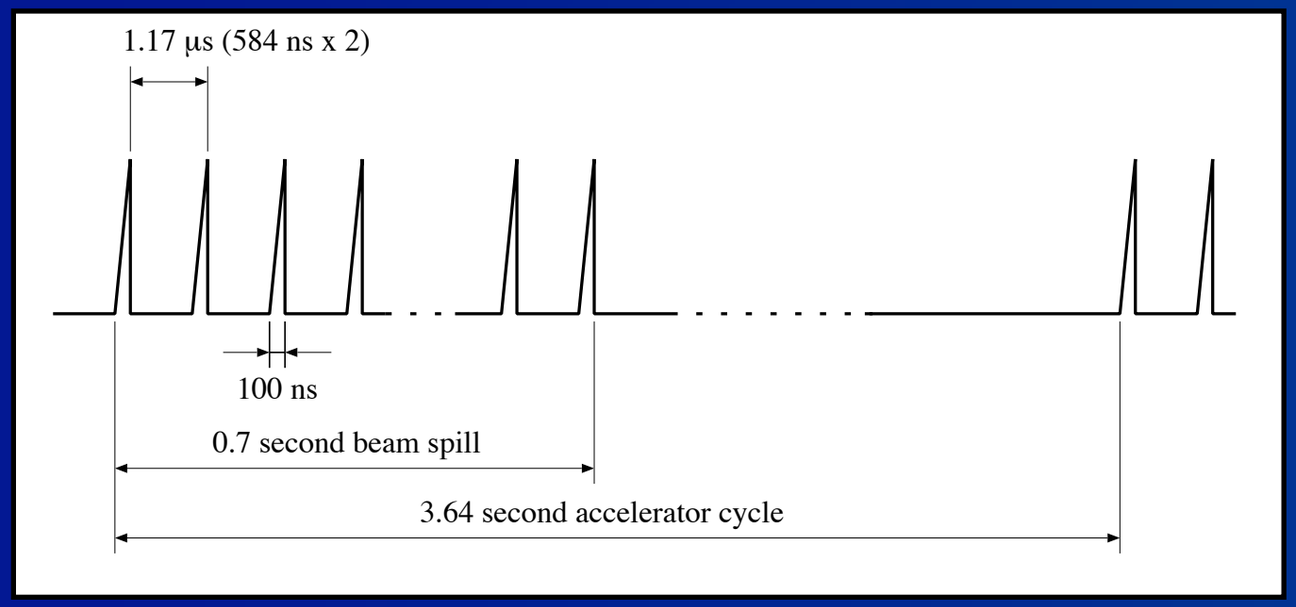
Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

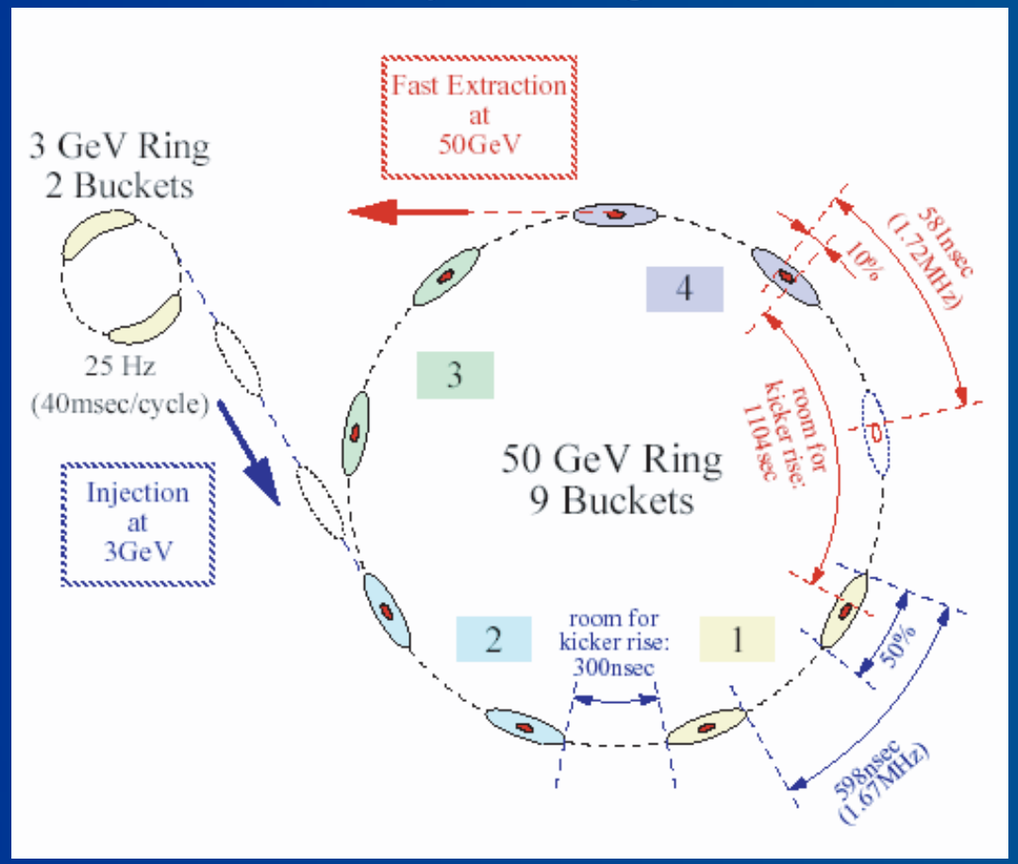
The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

Proton Beam (1)

- A pulsed proton beam is needed to reject beam-related prompt background.
  - Detection will be made between pulses (delayed measurement).
- Time structure required for proton beams.
  - Pulse separation is ~ 1μsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)

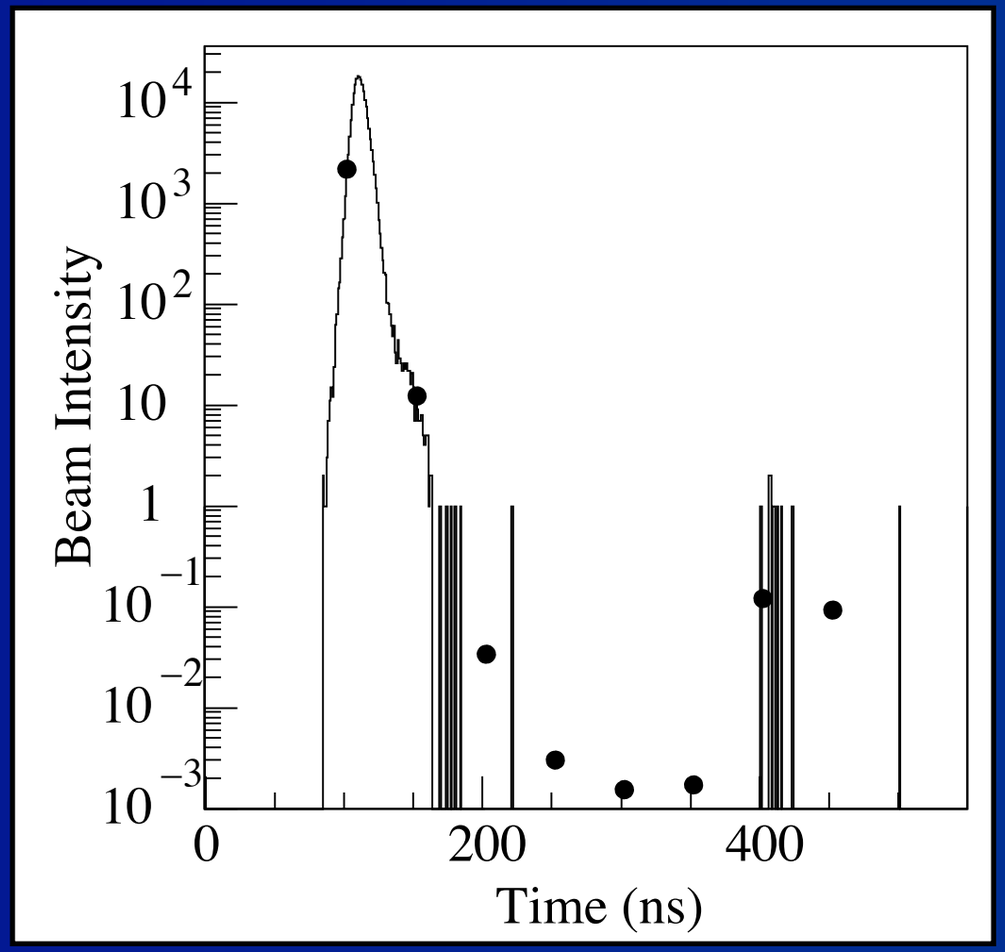


- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction with keeping bunches
  - spill length (flat top) ~ 0.7 sec
    - good to be shorter for cosmic-ray backgrounds.



Proton Beam (2) - 2 SSC years

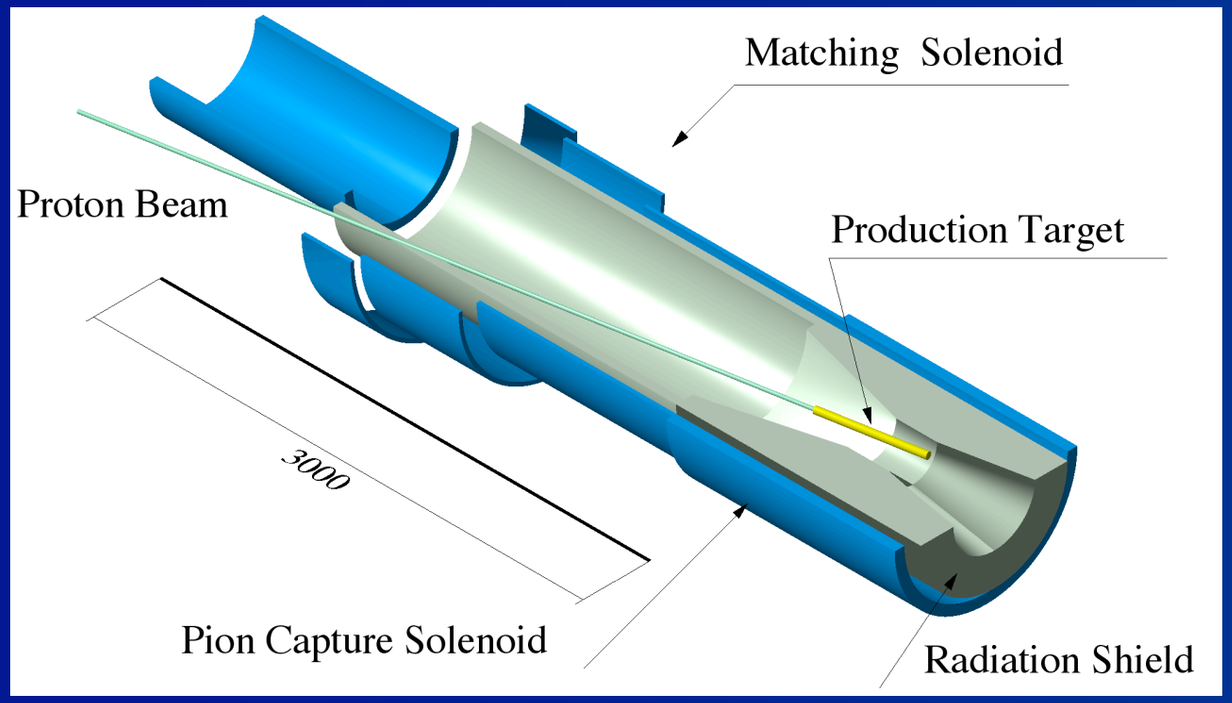
- Proton Extinction :
  - (delayed)/(prompt)<10^{-9}
  - Test done at BNL-AGS gave 10^{-7} (shown below).
  - Extra extinction devices are needed.
- Required Protons :
  - 8 x 10^{20} protons of 8 GeV in total for a single event sensitivity of about 0.3 x 10^{-16}.
  - For 2 x 10^{7} sec running, 4 x 10^{13} protons /sec (= 7 μA).
  - A total beam power is 56 kW, which is about 1/8 of the J-PARC full beam power of 450 kW (30 GeV x 15μA).



Test of Extinction at BNL-AGS

Pion Capture

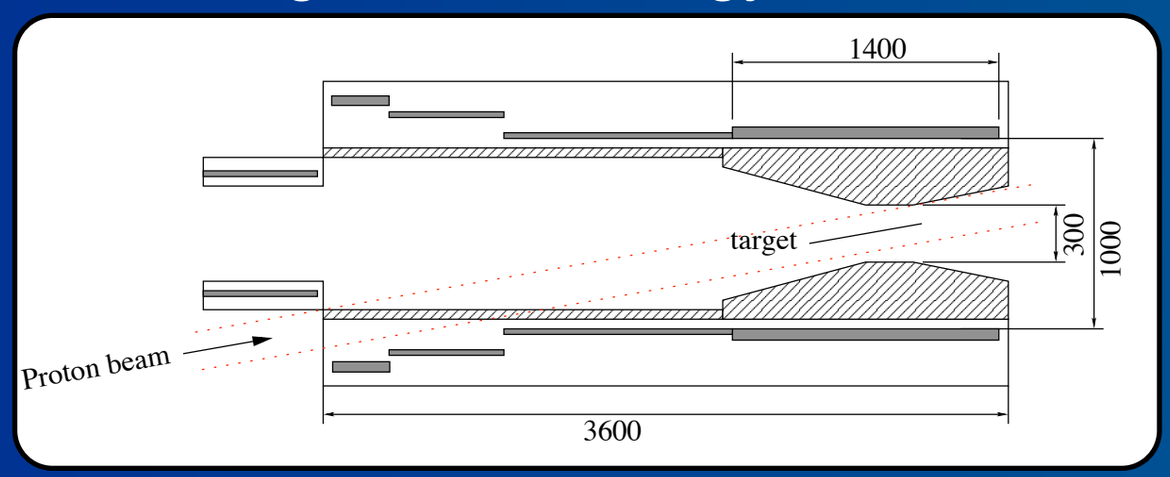
- A large muon yield can be achieved by large solid angle pion capture by a high solenoid field, which is produced by solenoid magnets surrounding the proton target.



$$P_T(GeV/c) = 0.3 \times B(T) \times (\frac{R(m)}{2})$$

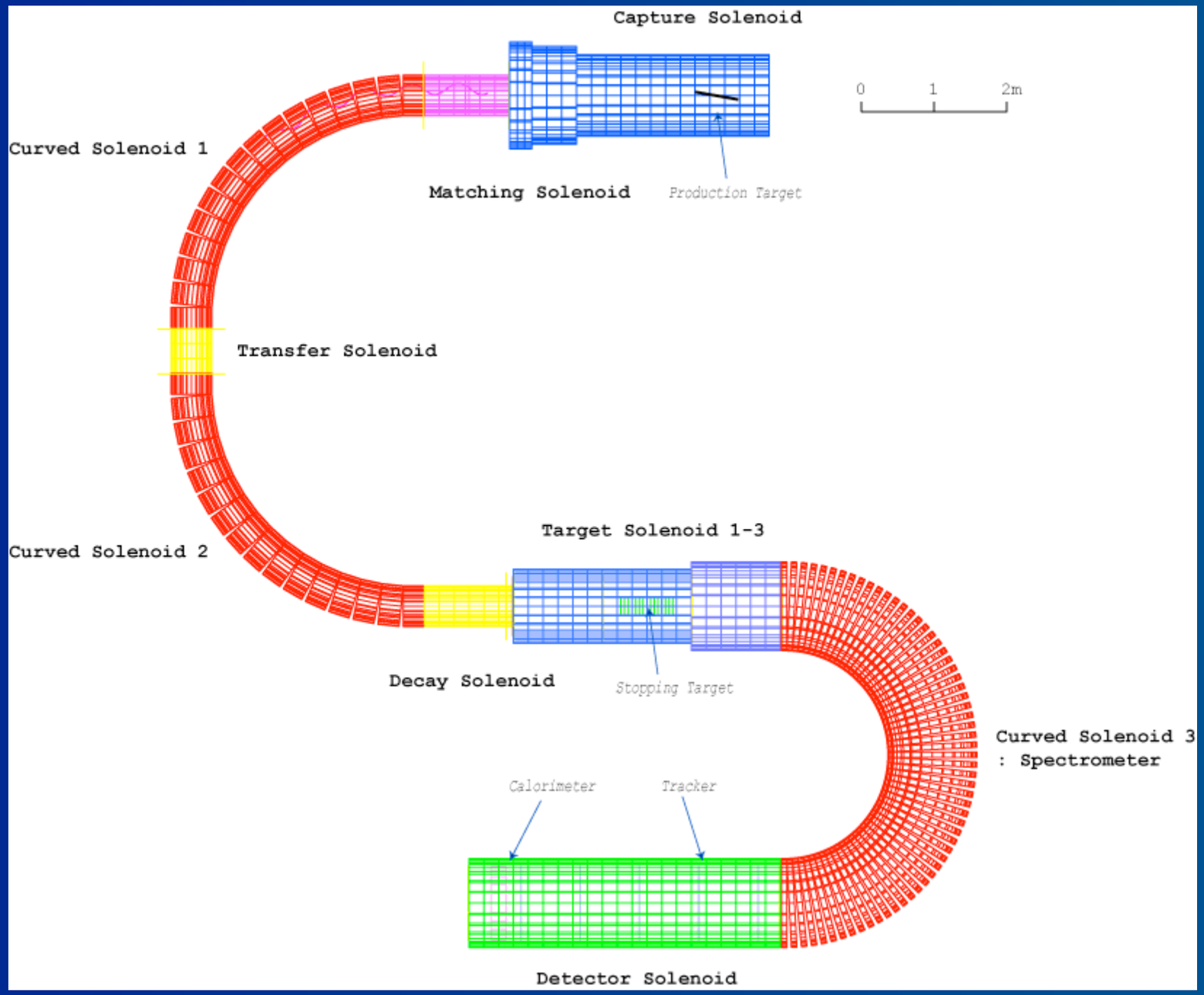
- B=5T,R=0.2m, P_T=150MeV/c.

- Superconducting Solenoid Magnet for pion capture
  - 15 cm radius bore
  - a 5 tesla solenoidal field
  - 30 cm thick tungsten radiation shield
  - heat load from radiation
  - a large stored energy



Muon Transport Beamline

- Muons are transported from the capture section to the detector by the muon transport beamline.
- Requirements :
  - long enough for pions to decay to muons (> 20 meters ≈ 2×10^{-3}).
  - high transport efficiency (P_μ~40 MeV/c)
  - negative charge selection
  - low momentum selection (P_μ<75 MeV/c)
- Straight + curved solenoid transport system is adopted.



Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

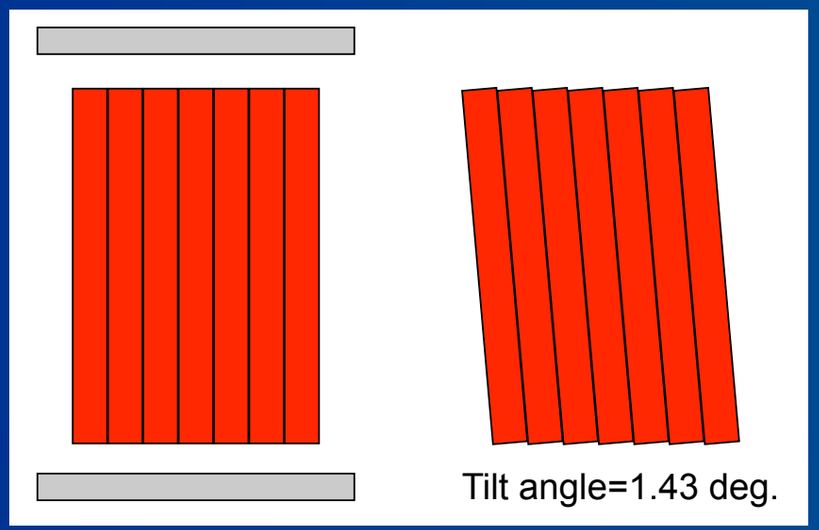
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(P_T/P_L)*

- This effect can be used for charge and momentum selection.

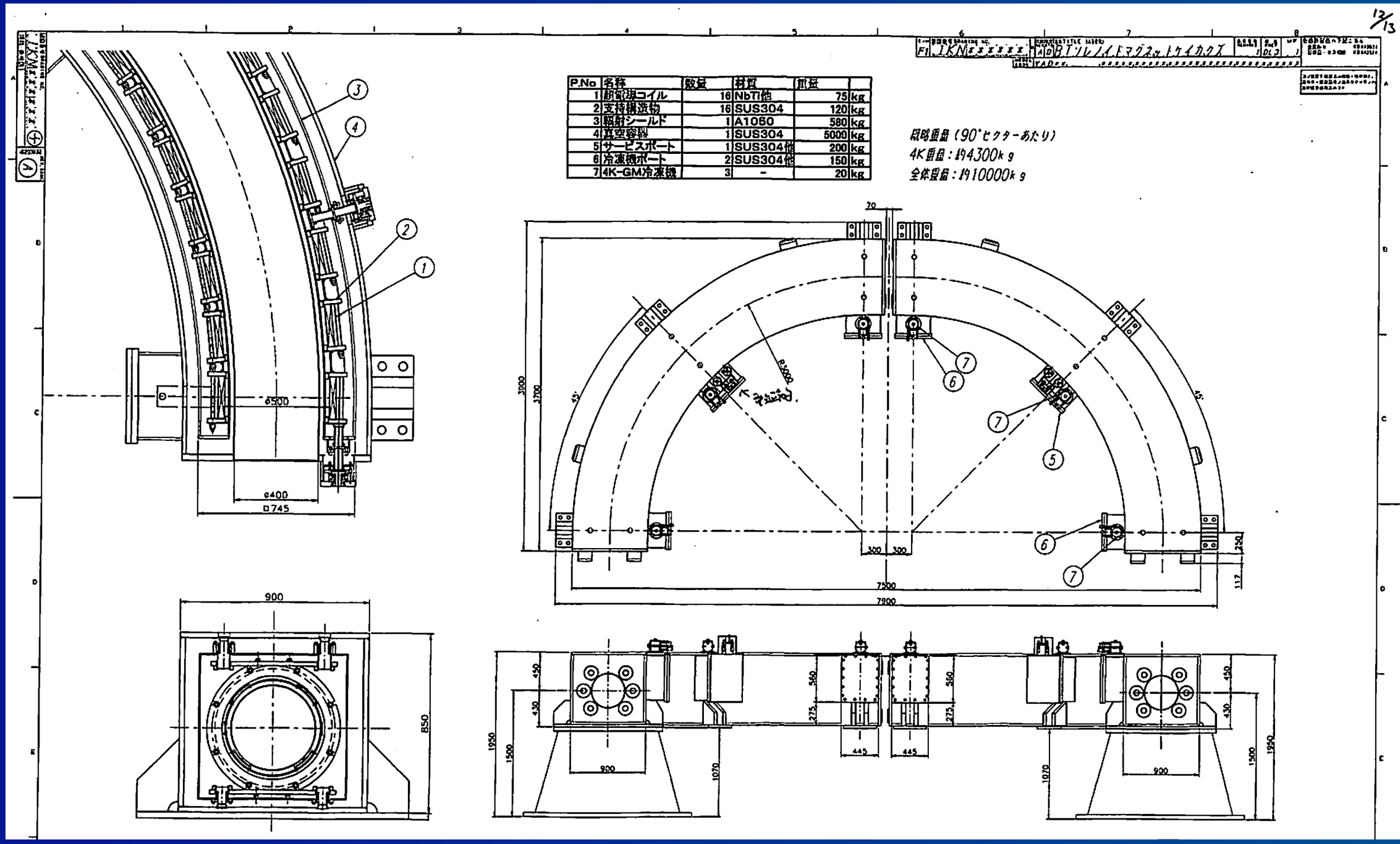
- This drift can be compensated by an auxiliary field parallel to the drift direction given by

$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ *: atan(P_T/P_L)*



Transport Solenoid Design



Spectra at the End of the Muon Transport

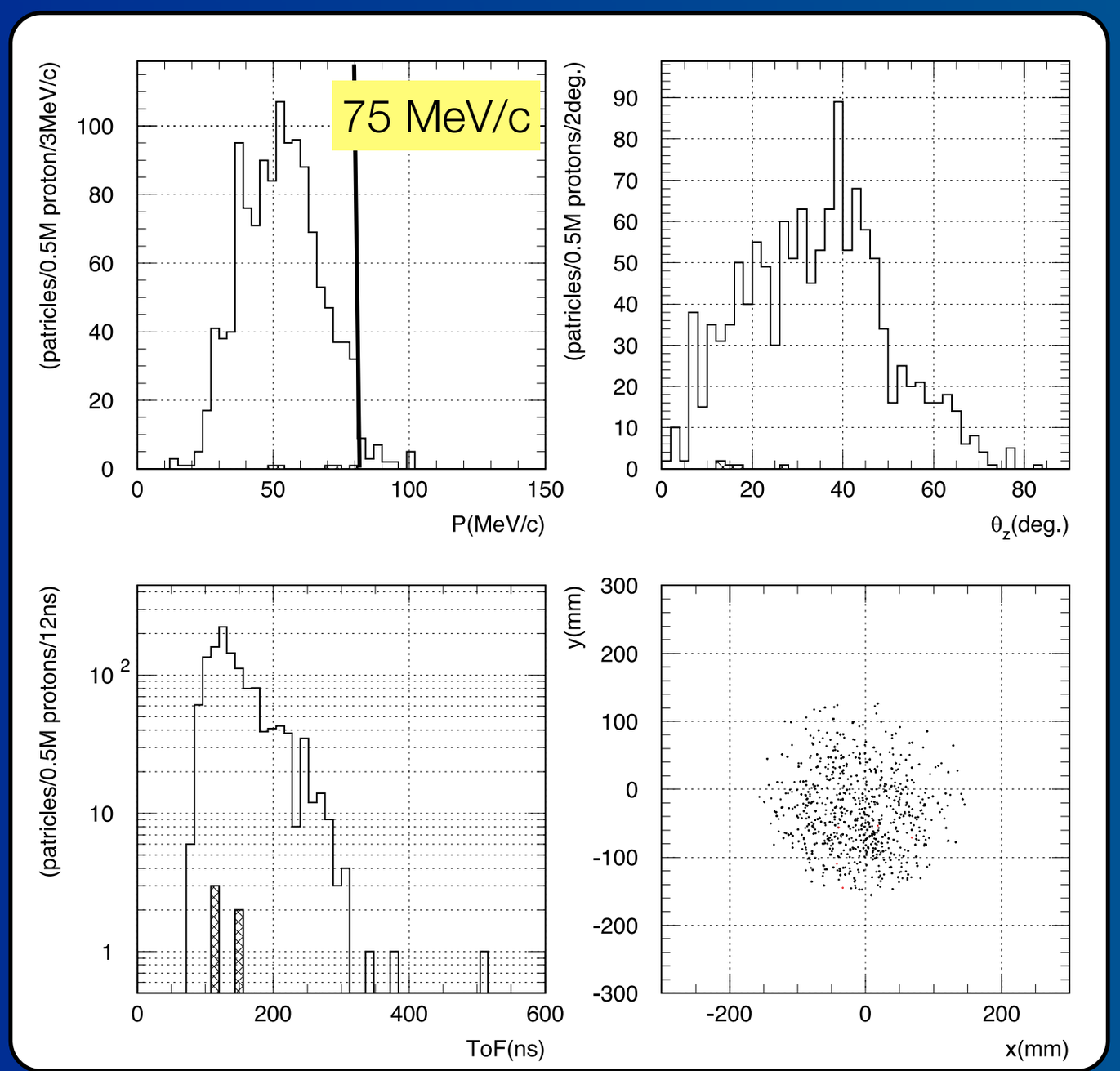
- Preliminary beamline design
  - main magnetic field
  - compensation field
  - radius of magnets (200 mm)

- Transport Efficiency

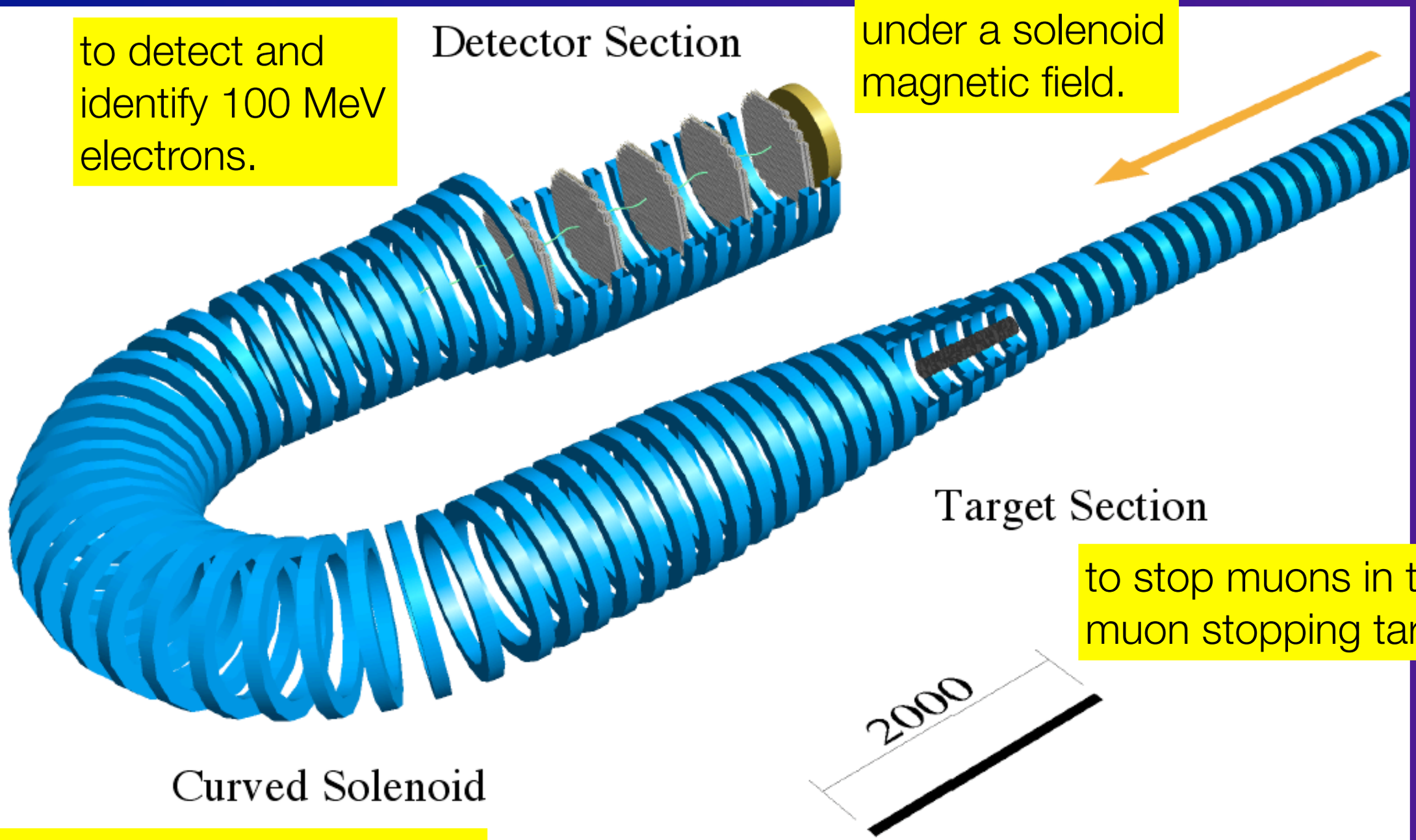
# of muons /proton	0.0071
# of stopped muons /proton	0.0018
# of muons of p_μ >75 MeV/c /proton	2×10^{-4}

Spectra at the end of the beamline

(top left) total momentum
(top right) direction angles to beam axis
(bottom left) time of flight
(bottom right) beam profile
muons for open histograms, pions for hatched histograms.



to detect and identify 100 MeV electrons.



under a solenoid magnetic field.

to stop muons in the muon stopping target.

to eliminate low-energy beam particles and to transport only ~100 MeV electrons.

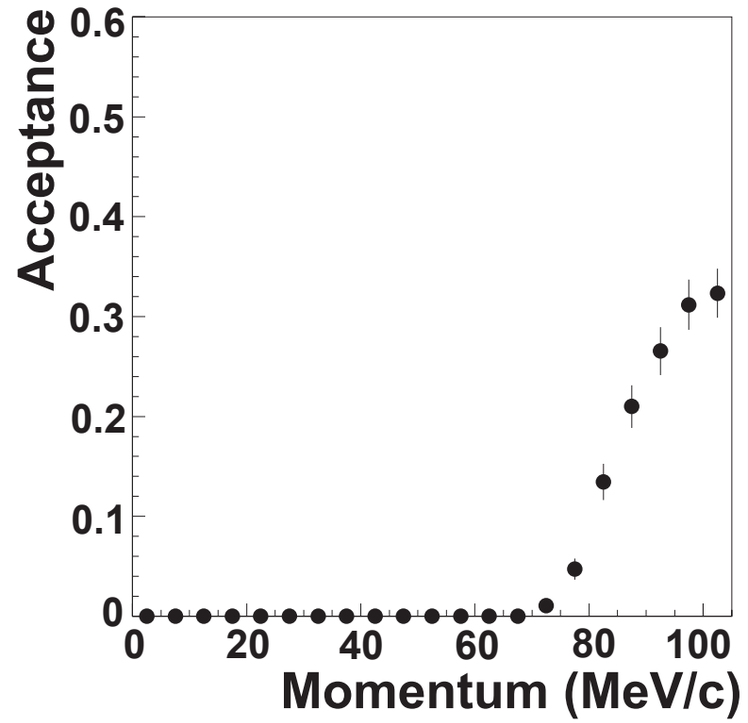
Detector Components

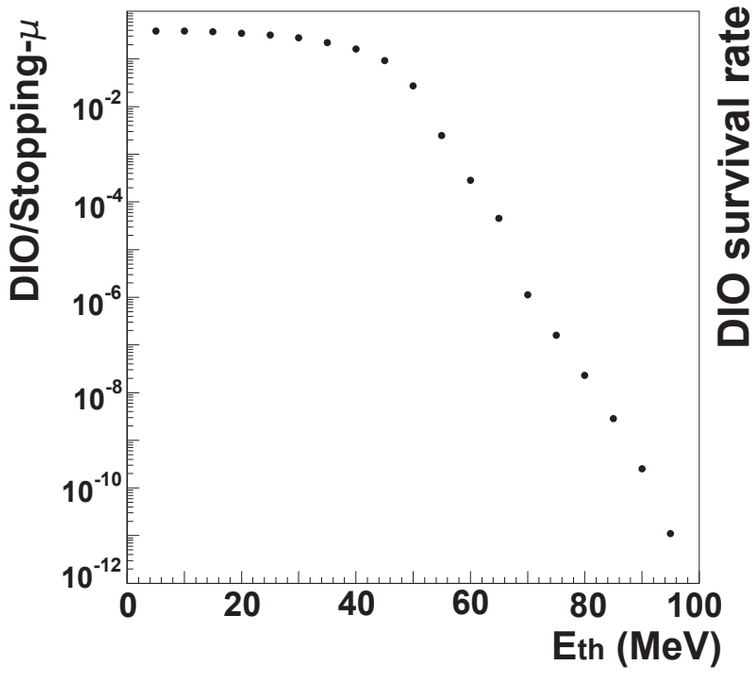
a muon stopping target, curved solenoid,tracking chambers, and a calorimeter/trigger and cosmic-ray shields.

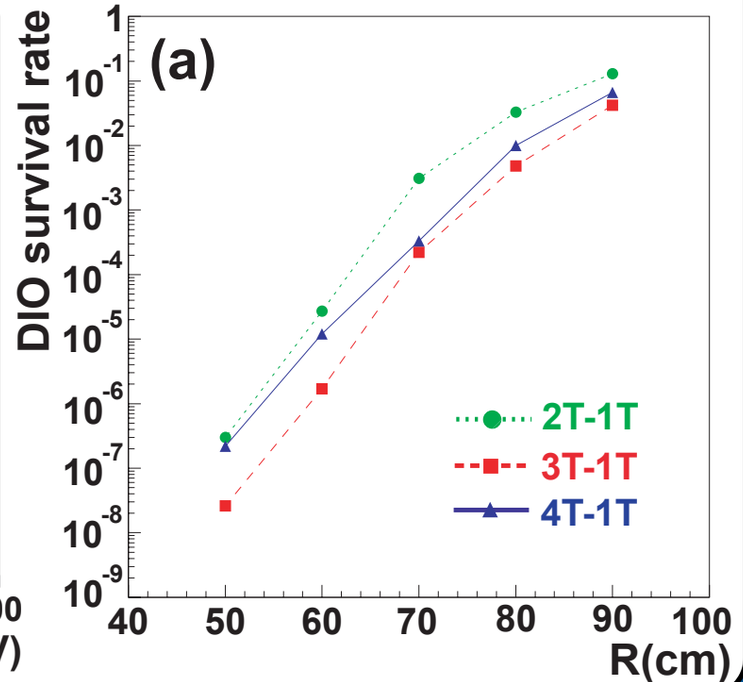
Transmission of the Electron Transport

- Electron Transport System Parameters (preliminary)
  - Radius : 50 cm
  - Magnetic field : 1 Tesla
  - Bending angle : 180 degrees
- Geometrical Acceptance
  - Solid angel at the target : 0.73
    - mirror effect at a graded field
  - Transport efficiency : 0.44
  - Total : 0.32
- Suppression of electrons from decay in orbit.
  - about 10^{-8} suppression
  - about 1000-10000 tracks / sec for 10^{11} stopping muons.

Ratio of a number of electrons reaching the end of transport to all electrons emitted in 4π.





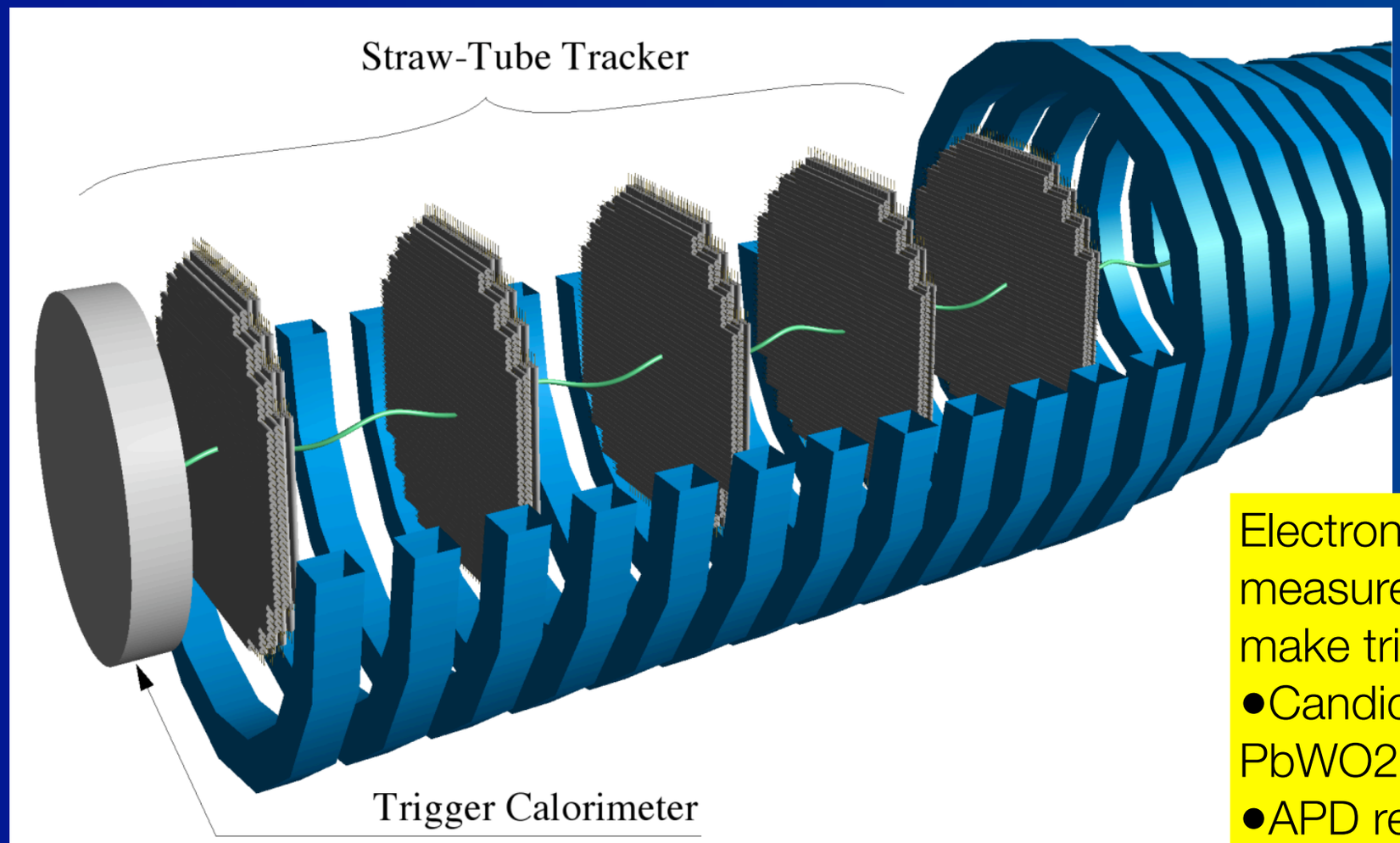


Electron Detection (preliminary)

Straw-tube Trackers to measure electron momentum.
- should work in vacuum and under a magnetic field.
- A straw tube has 25μm thick, 5 mm diameter.
- One plane has 2 views (x and y) with 2 layers per view.
- Five planes are placed with 48 cm distance.
- 250μm position resolution.

Under a solenoidal magnetic field of 1 Tesla.

In vacuum to reduce multiple scattering.

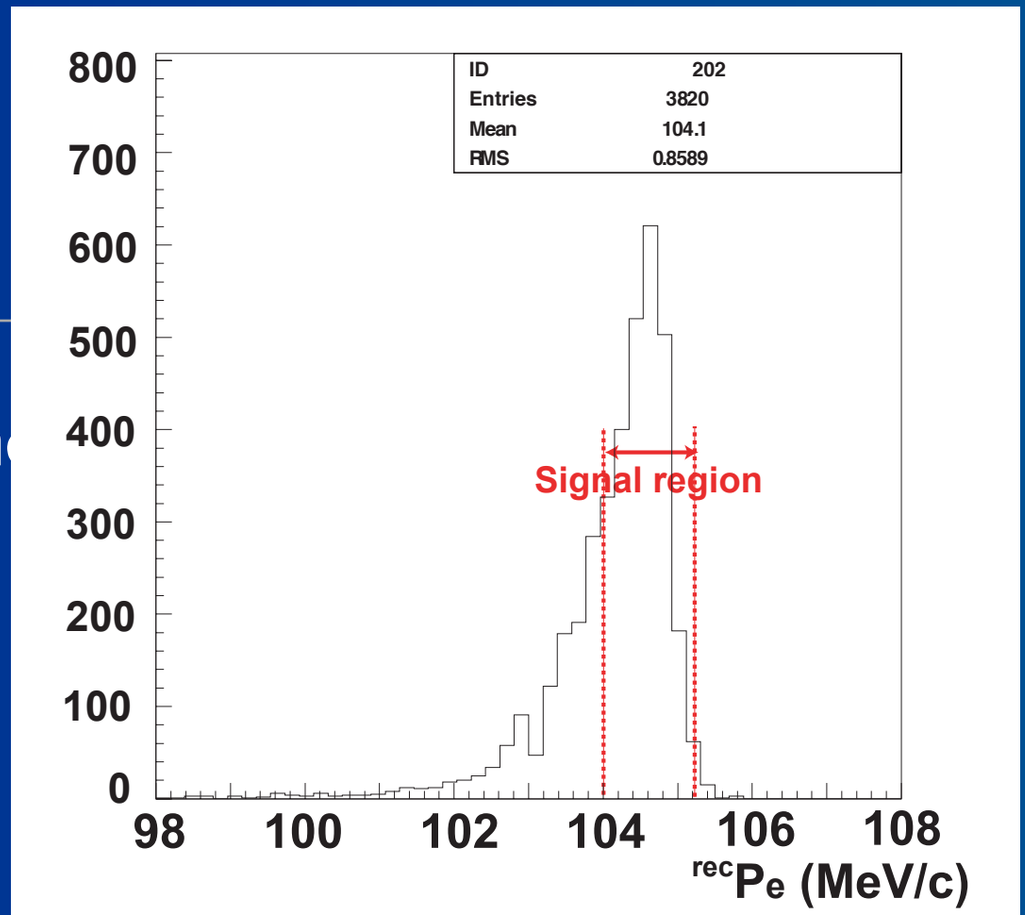


Electron calorimeter to measure electron energy and make triggers.
- Candidate are GSO or PbWO2.
- APD readout (no PMT).

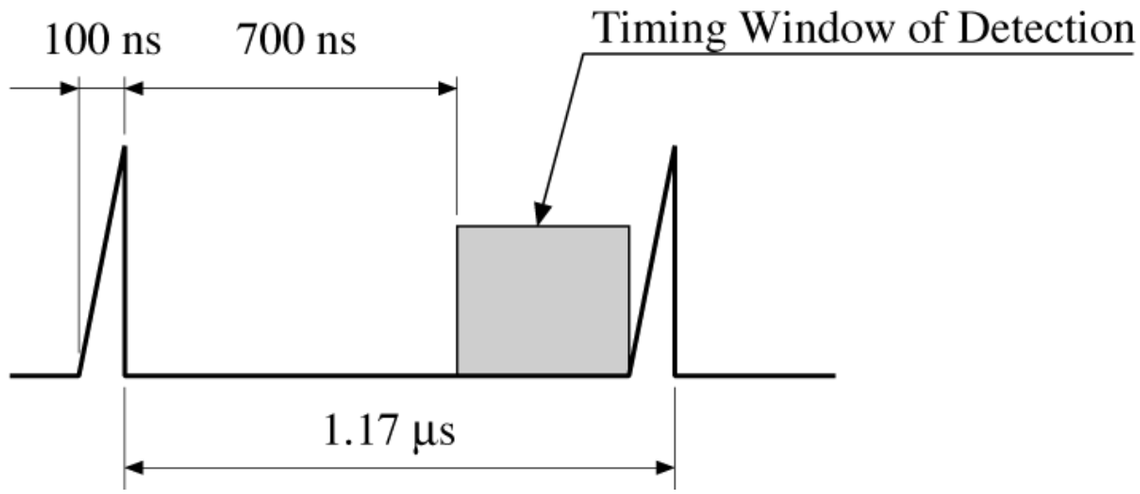
Signal Acceptance

- The signal acceptance is given by the geom
  and the analysis (cut) acceptance.

Items	Acceptance
geometrical	
solid angle at target	0.73
transport efficiency	0.44
analysis	
p_t > 52 MeV/c cut	0.67
chi2 cut	0.86
energy cut	0.56
time window cut	0.38
total	0.04



signal energy window (104.0-105.2 MeV in uncorrected energy scale)



Signal Sensitivity (preliminary) - 2 SSC years

- Single event sensitivity

$$B(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is 1.5x10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

Tungsten target & beam line optimzation → improvement of x2.7

total protons	8x10^{20}
muon transport efficiency	0.0071
muon stopping efficiency	0.26
# of stopped muons	1.5x10^{18}

$$B(\mu^- + Al \to e^- + Al) = \frac{1}{1.5 \times 10^{18} \times 0.6 \times 0.04} = 2.8 \times 10^{-17}$$

$$B(\mu^- + Al \to e^- + Al) < 5 \times 10^{-17} \quad (90\%\ \mathrm{C.L.})$$

Potential Background Events

- Background rejection is the most important in searches for rare decays.
- Types of backgrounds for $\mu^- + N \rightarrow e^- + N$ are,

Intrinsic backgrounds	originate from muons stopping in the muon stopping target.	●muon decay in orbit ●radiative muon capture ●muon capture with particle emission
Beam-related backgrounds	caused by beam particles, such as electrons, pions, muons, and anti-protons in a beam	●radiative pion capture ●muon decay in flight ●pion decay in flight ●beam electrons ●neutron induced ●antiproton induced
Other backgrounds	caused by cosmic rays	●cosmic-ray induced ●pattern recognition error

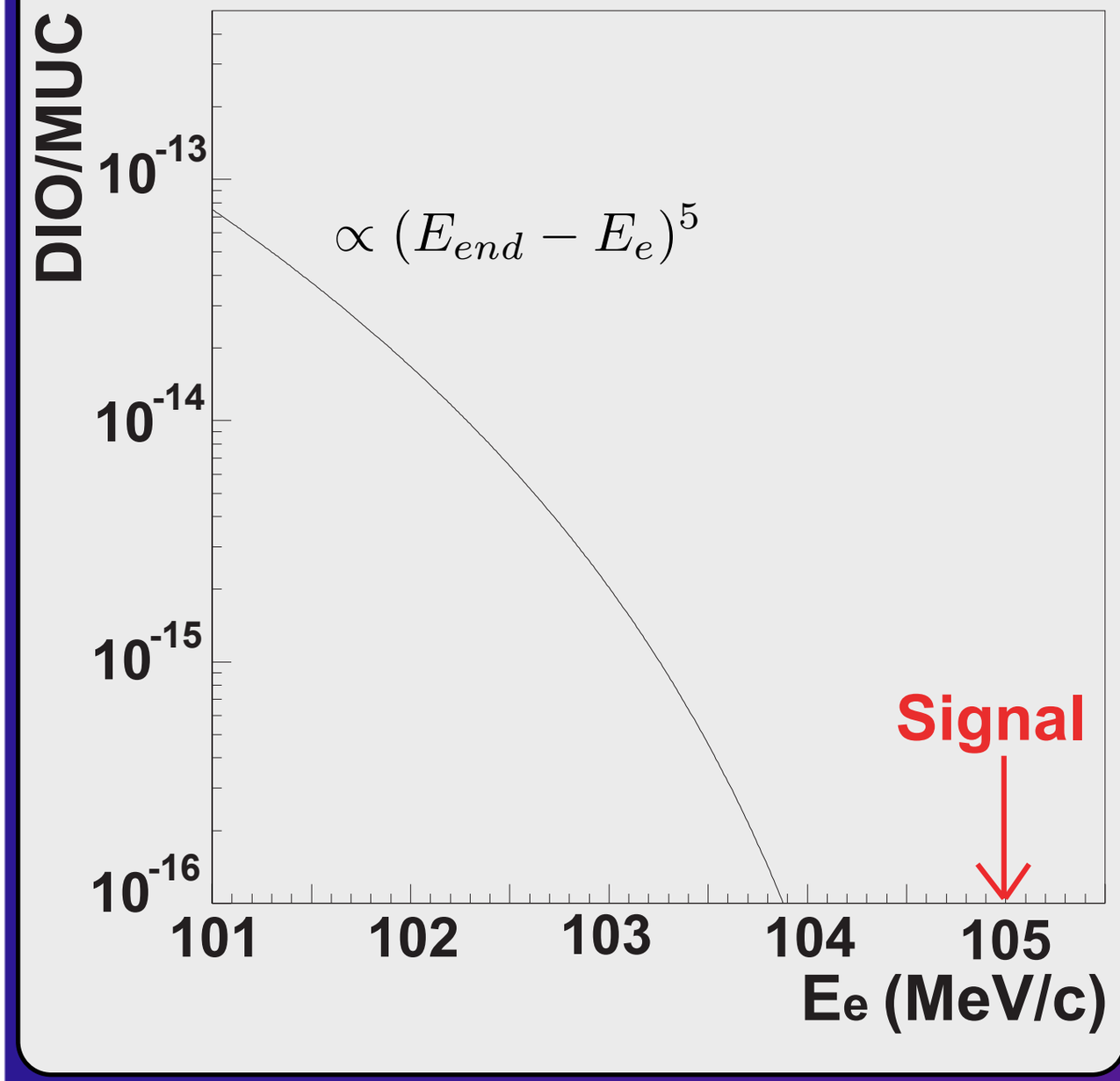
Intrinsic Background (from muons)

- Muon Decay in Orbit
  - Electron spectrum from muon decay in orbit
  - Response function of the spectrometer included.
  - 0.05 events in the signal region of 104.0 - 105.2 MeV (uncorrected).
- Radiative Muon Capture with Photon Conversion

$$\mu^- + Al \rightarrow \nu_\mu + Mg + \gamma$$

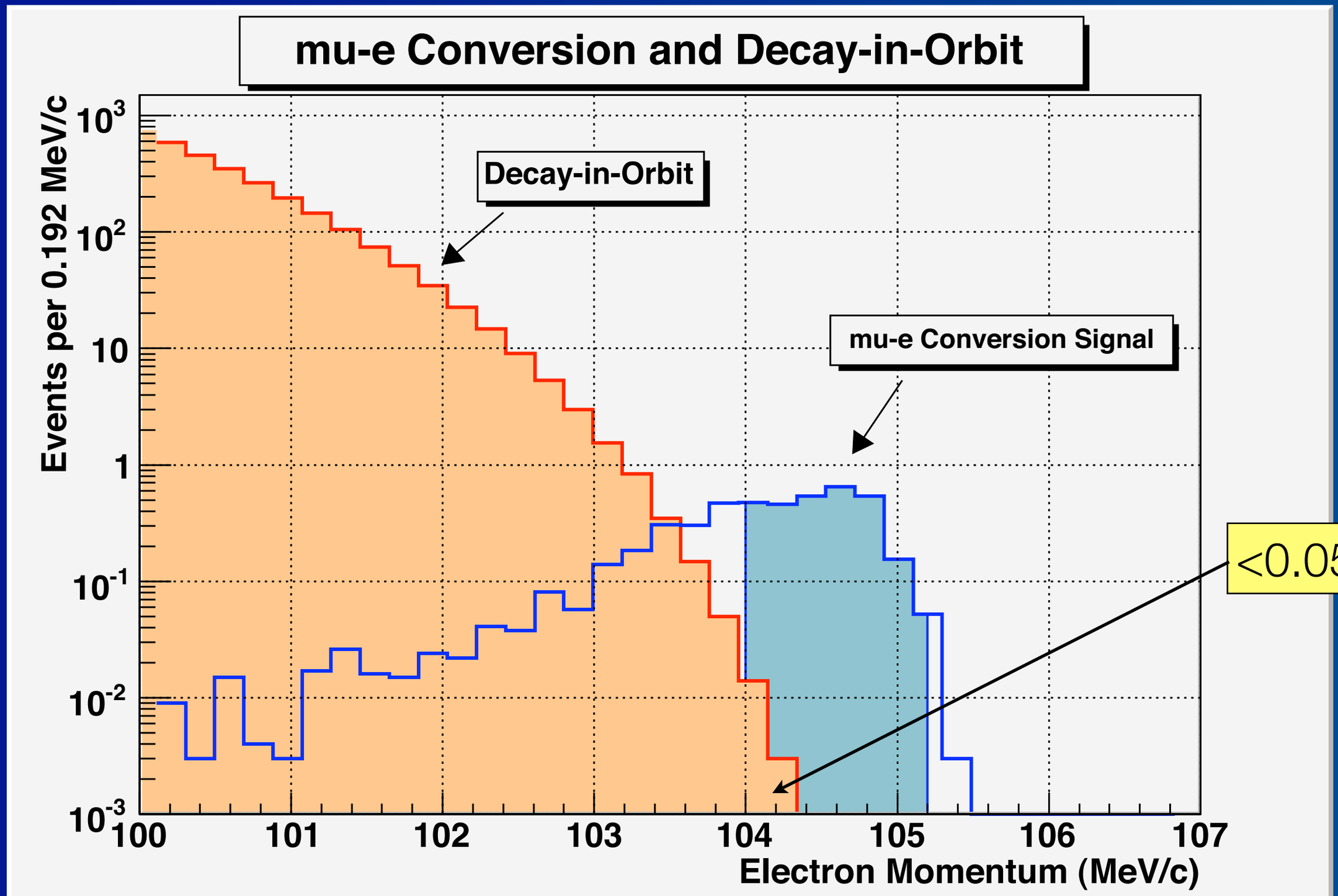
  - Max photon energy 102.5 MeV
  - < 0.001 events
- Muon Capture with Neutron Emission
- Muon Capture with Charged Particle Emission
  - <0.001 events for both.

Energy spectrum of electrons from decays in orbit in a muonic atom of aluminum, as a function of electron energy. The vertical axis shows the effective branching ratio of μ-e conversion.



DIO Background

a number of events for
1.1 x10^{18} stopped muons.



BG with asterisk needs beam extinction.

Background Rejection Summary (Preliminary)

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.10	10^{-4} veto & 2×10^{7}sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

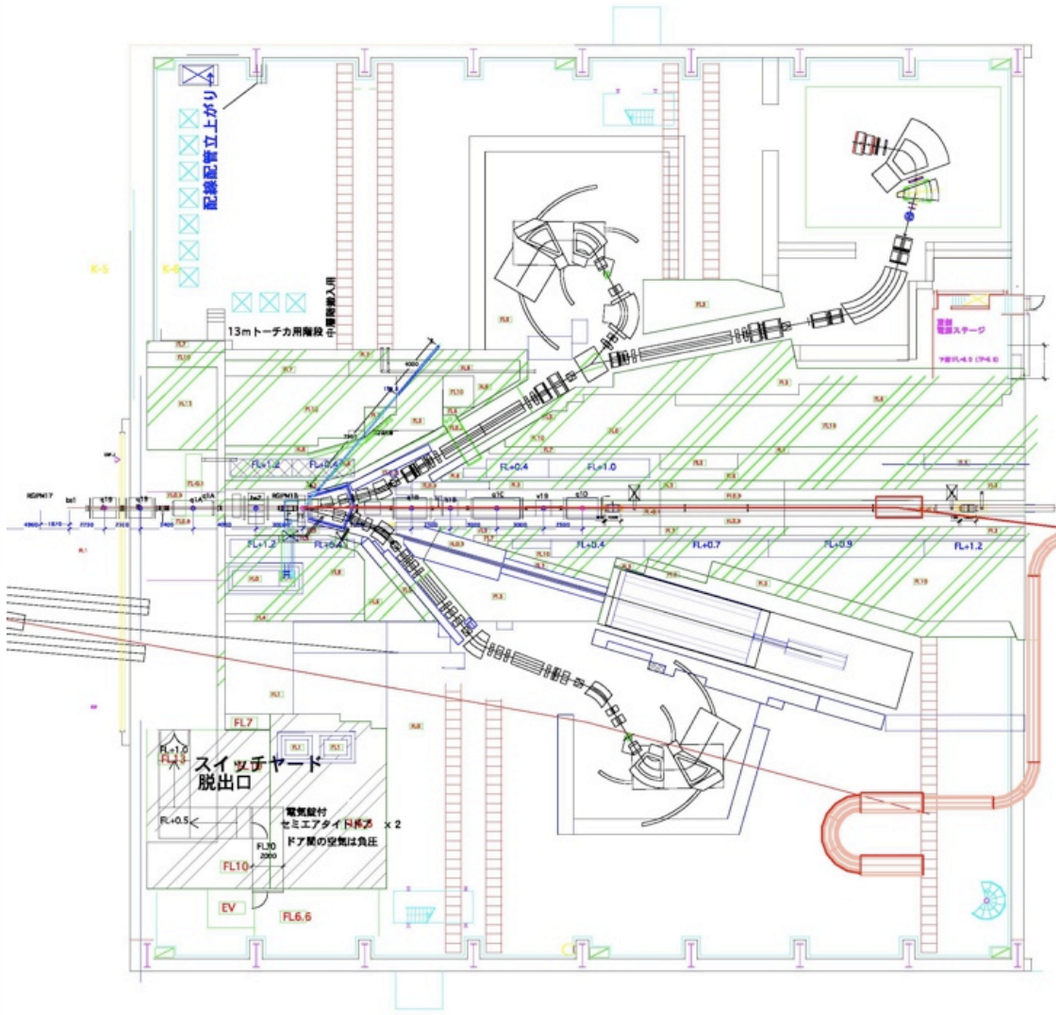
Report from the J-PARC PAC Meeting Jan. 2008

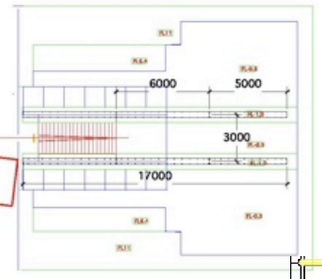
One of the flagship experiments in the J-PARC programs.

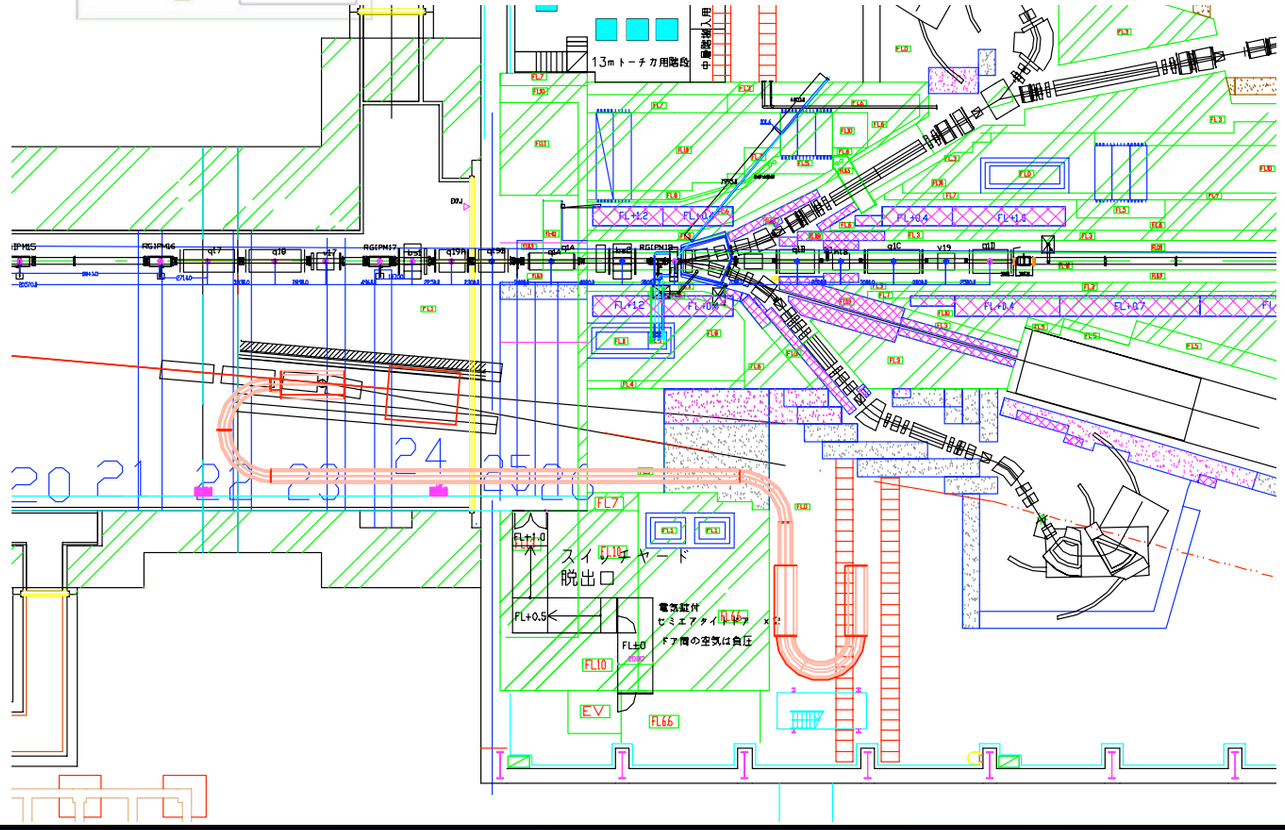
from Minutes of the 4th PAC meeting, Draft (March.01) cont.

The PAC is impressed with the physics capabilities of the proposed COMET experiment and believes that this experiment could become one of the flagship experiments in the J-PARC program. On the other hand, this is a very difficult experiment and will demand large resources from the collaboration and the laboratory. A detailed assessment by the PAC and Laboratory of the feasibility for making such a precise measurement will need a more detailed design and simulation of the experiment. For these reasons, the PAC asks for more information to be provided over the next several meetings on the design, capability, and schedule for the experiment. This information and answers to the questions posed below should be given in an addendum to the proposal and presentations should be given at the next meeting if possible. Preliminary interactions should

Possible Layout at the NP Hall





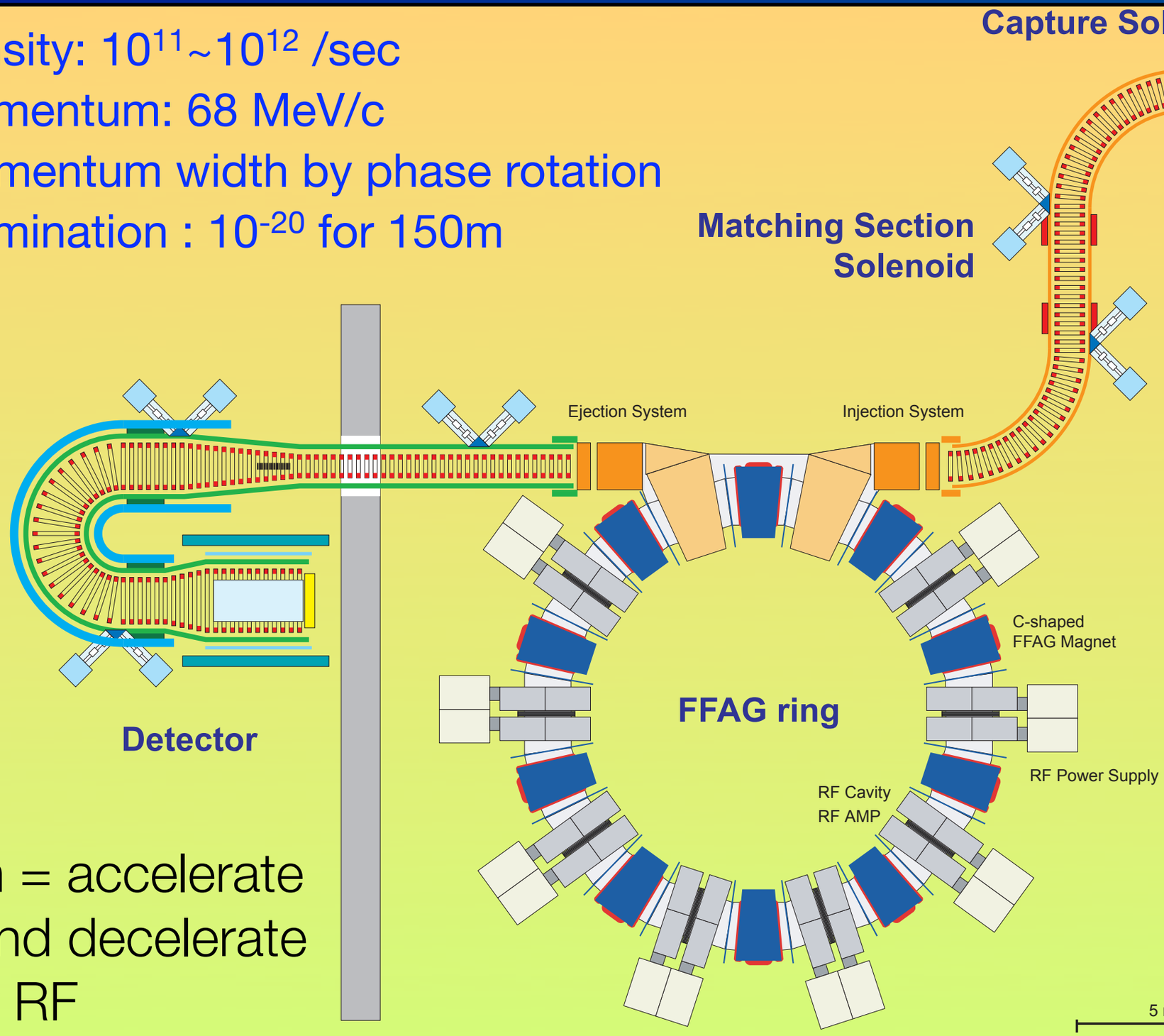


PRISM

PRISM Muon Beam

PRISM=Phase Rotated
Intense Slow Muon source

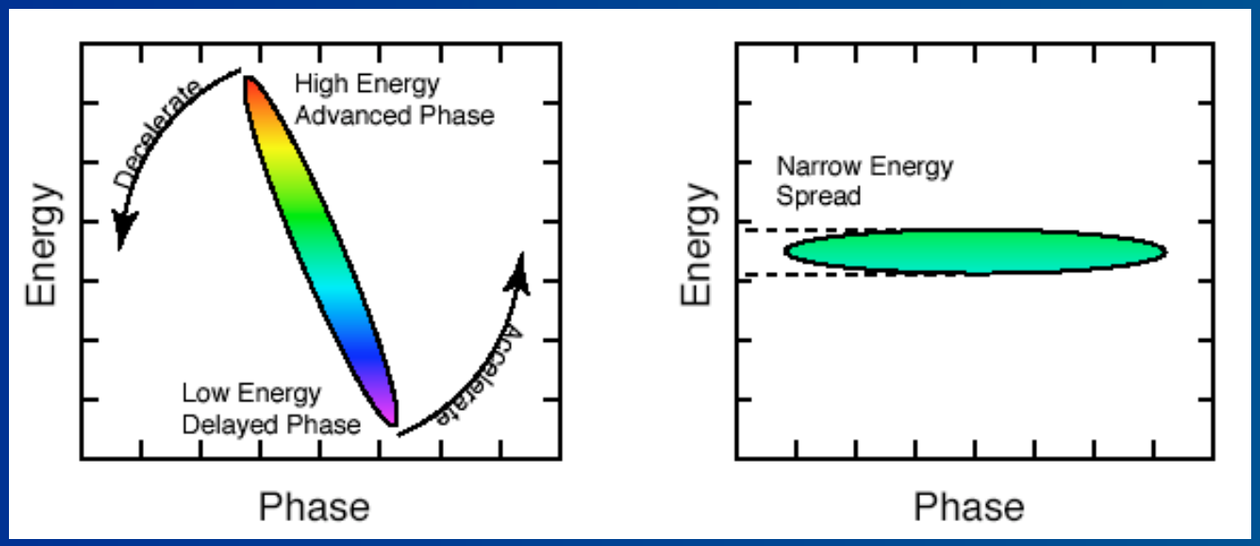
- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF

... To Make Narrow Beam Energy Spread

- A technique of phase rotation is adopted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles.
- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
  - Fast particle comes earlier and slow particle comes late.
- Proton beam pulse should be narrow (< 10 nsec).
- Phase rotation is a well-established technique, but how to apply a tertiary beam like muons (broad emittance) ?



Phase Rotation for a Muon Beam

Use a muon storage ring ?

(1) Use a muon Storage Ring :
A muon storage ring would be better and realistic than a linac option because of reduction of # of cavities and rf power.
(2) Rejection of pions in a beam :
At the same time, pions in a beam would decay out owing to long flight length.

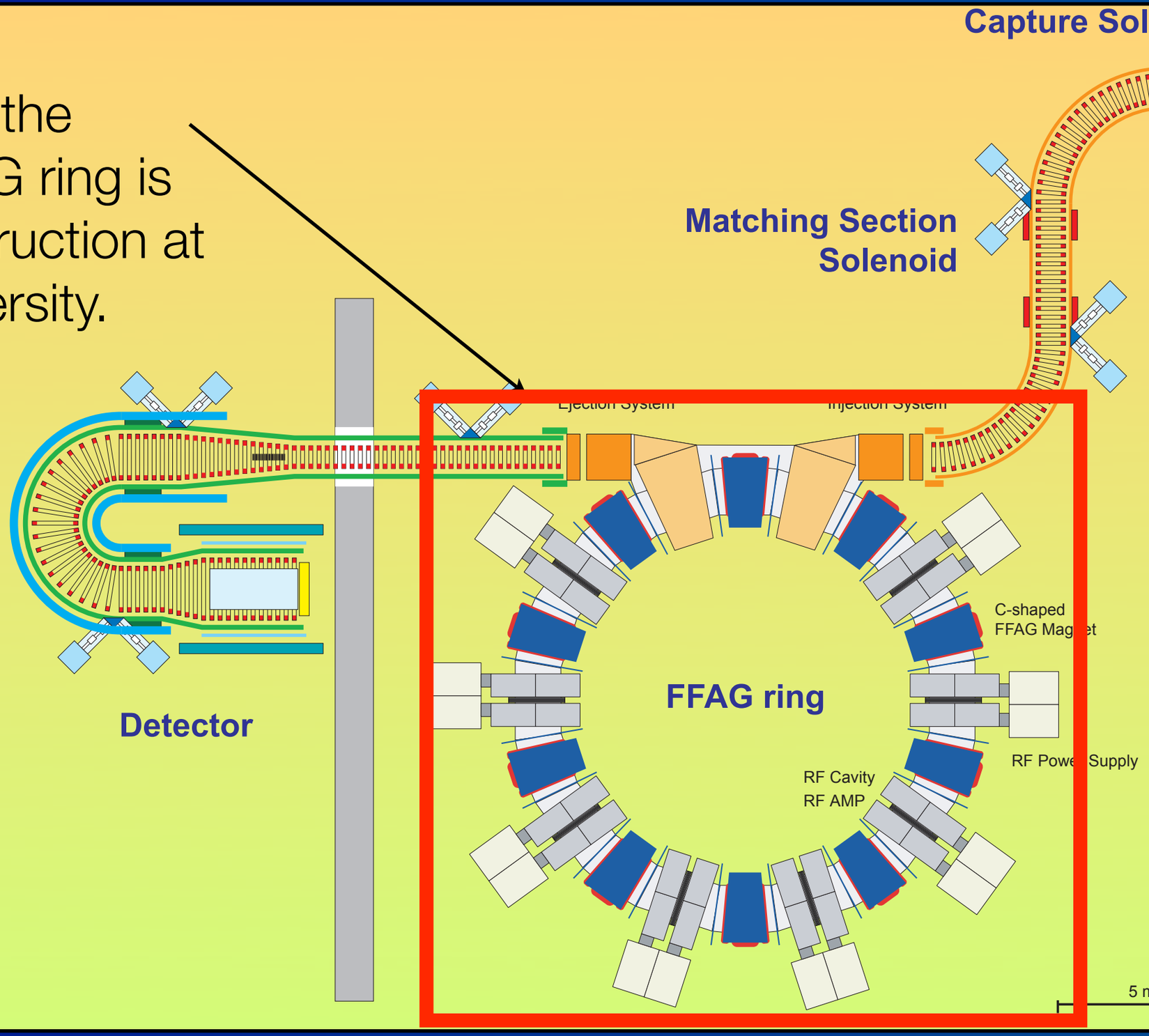
Which type of a storage ring ?

(1) cannot be cyclotron, because of no synchrotron oscillation.
(2) cannot be synchrotron, because of small acceptance and slow acceleration.

Fixed field Alternating Gradient Ring (FFAG)

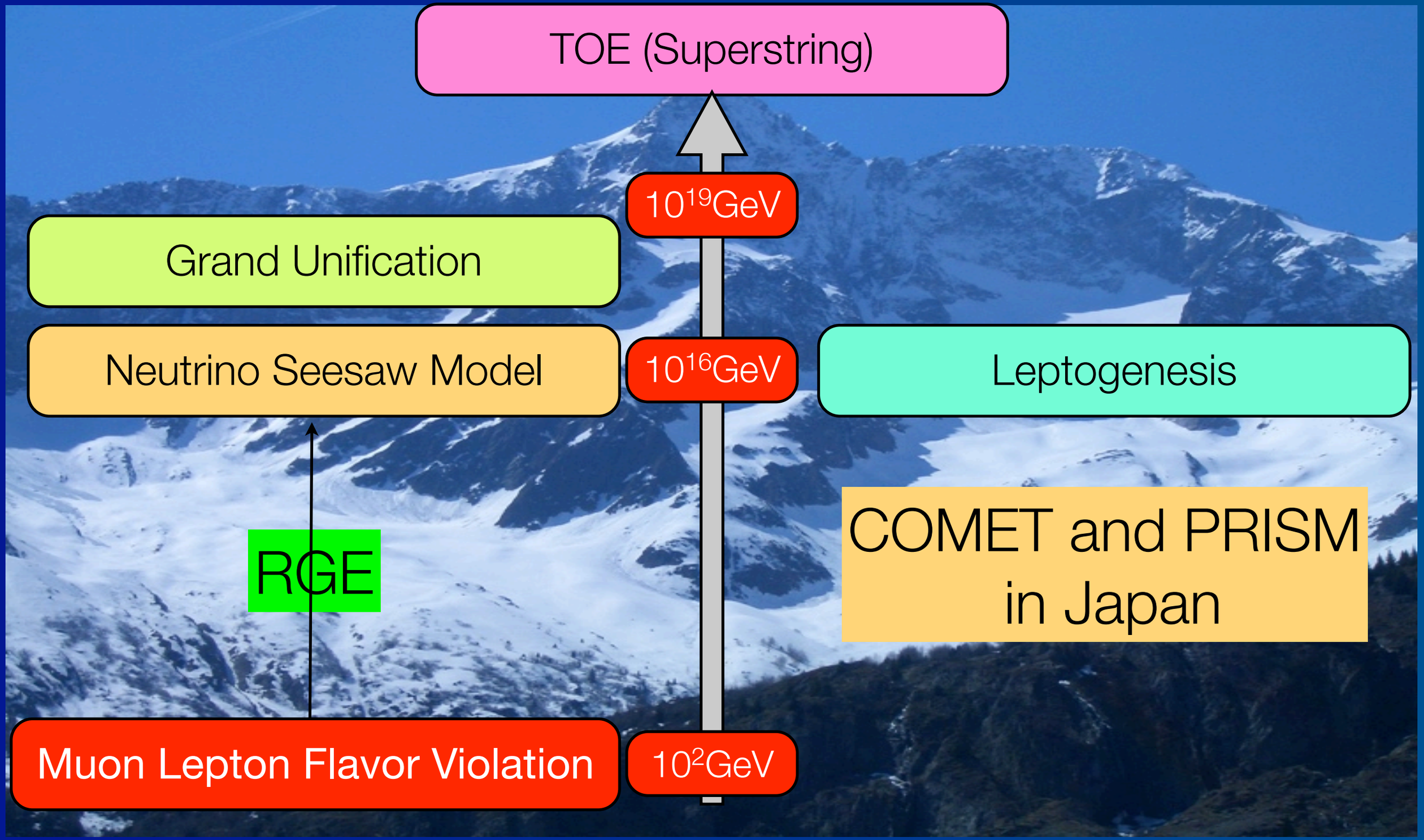
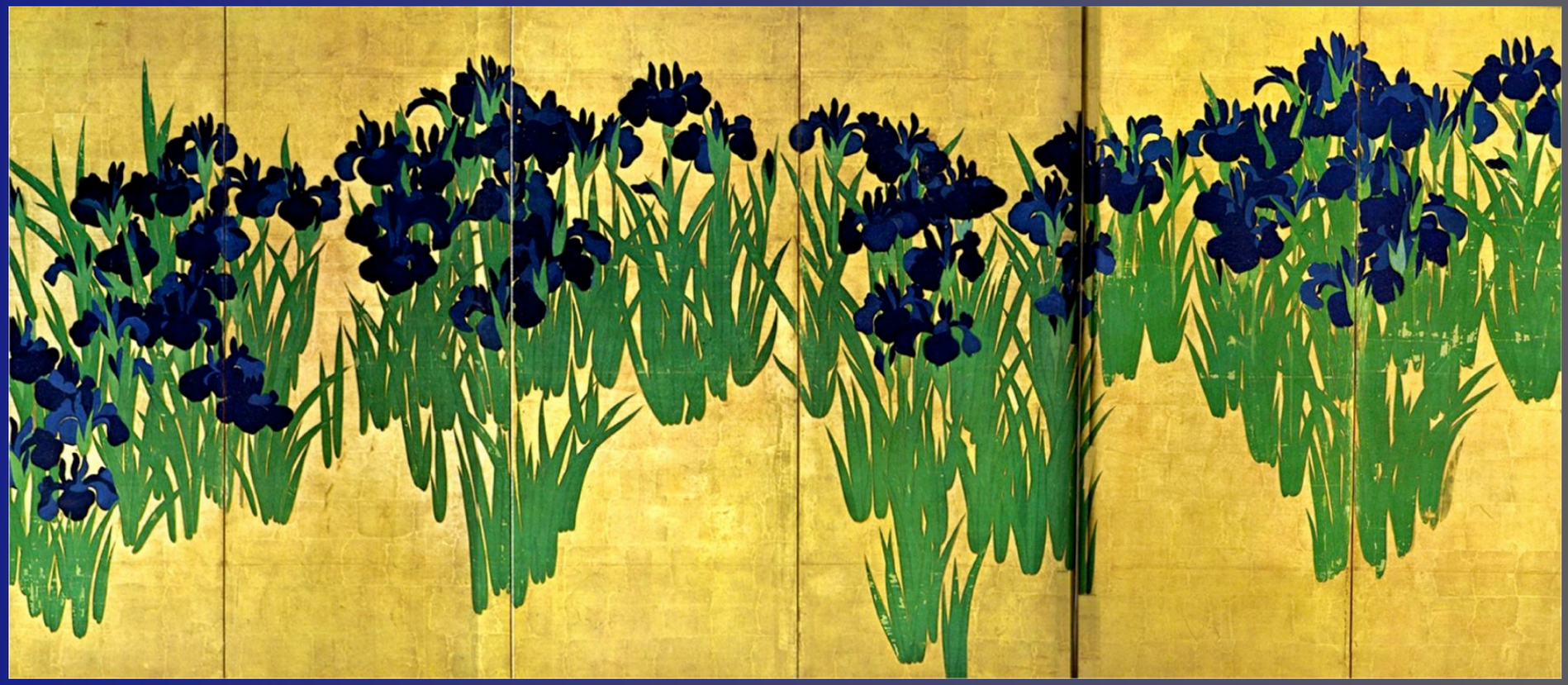
PRISM FFAG Ring R&D

A portion of the PRISM-FFAG ring is under construction at Osaka University.



R&D on the PRISM Muon Storage (FFAG) Ring at Osaka University

Summary


TOE (Superstring)
10^{19}GeV
Grand Unification
Neutrino Seesaw Model
10^{16}GeV
Leptogenesis
RGE
COMET and PRISM
in Japan
Muon Lepton Flavor Violation
10^{2}GeV

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